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GENERALIZED SELECTION CHARTS FOR BOMBERS

POWERED BY TWO, FOUR, AND SIX 3000-HORSEPOWER ENGINES

By Maurice J. Brevoort, George W. Stickle, and Paul R. Hill

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NACA

WASHINGTON

MEMORANDUM REPORT

for

Army Air Forces, Materiel Command

GENERALIZED SELECTION CHARTS FOR BOMBERS

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INTRODUCTION

This report is one of a series of reports (references 1 and 2) relating the parameters of airplanes to their performance. Reference 1 is the basic report that presents the methods of analysis. Two degrees of aerodynamic refinement are presented for comparison: one represents the best that can be constructed today with the present amount of defensive armament, and the other represents a reduction of aerodynamic drag to show the improvement in performance with reduction of drag. The lower aerodynamic drag may represent airplanes that will be built several years in the future.

Reference 2 presents an analysis of the relationship of the parameters and the performance of airplanes powered by one, two, four, and six 2000-horsepower engines supercharged to 25,000 feet altitude.

The subject report presents the relationship of the parameters and the performance of airplanes powered with two, four, and six 3000-horsepower engines supercharged to 35,000 feet altitude. This report is similar to that of reference 2 except the 2000-horsepower engines supercharged to 25,000 feet are replaced by 3000-horsepower engines supercharged to 35,000 feet. Charts for two degrees of aerodynamic refinement are presented as was done in reference 1.

Range, speed, rate of climb, and take-off distances are presented on charts with coordinates of power loading and wing loading, and are summarized for each family of bombers by composite charts called performance selection charts. From these charts the possible combinations of performances and the appropriate power loading and wing loading can be read.

The effect of the number of engines on performance trends at constant power loading is shown and a brief discussion of the factors creating these trends is given.

The assumptions and values of selected parameters upon which the charts are based are given in the appendix. A discussion of the methods of computation is given in reference 1 and is not repeated in this report.

SYMBOLS

b wing span, feet

C_1 coefficient multiplying the distributed load to give the effective distributed load

C_{D_o} parasite drag coefficient

F effective frontal area of the bodies of an airplane, square feet

f	design-load factor
K	wing-weight coefficient
L/D	lift-to-drag ratio
R	aspect ratio
S	wing area, square feet
t	root-wing thickness divided by root chord
W	gross weight of airplane, pounds
W_1	wing weight, pounds
W_2	distributed weight on the wing, pounds

PRESENTATION OF CHARTS

Charts showing the performance trends in range, speed, rate of climb, and take-off distance plotted on coordinates of power loading are given in figure 1. Each point on these charts defines a complete and consistent airplane. The aerodynamic and structural parameters have been varied in a consistent manner so that airplanes have equal load factors, wing-thickness ratio, aspect ratio, propeller efficiency, and aerodynamic cleanliness. These charts show performances that are aerodynamically and structurally consistent with the best airplanes that can be produced at the present time. The airplanes are all powered by 3000-horsepower engines supercharged to 35,000 feet altitude. Hence the speed curves are calculated for 35,000 feet altitude, but the range, rate-of-climb, and take-off-distance curves are calculated for sea level. (See the appendix.)

Figure 1(a) applies to two-engine bombers; figure 1(b), to four-engine bombers; and figure 1(c), to six-engine bombers. Cross plots from these charts show the trends in performance. Comparisons for a few special cases where the take-off distance is fixed at 4000 feet are given in figure 2. Take-off distances are given in figure 3.

Separate charts for each performance characteristic are given in figures 4 to 7. The performance characteristic can be read with greater accuracy than from the composite charts of figure 1. Included in this group are charts giving the maximum L/D and charts giving the structural weights and carrying capacity of gasoline, oil, and bombs.

Figures 10(a), 10(b), and 10(c) give performance selection charts for two-, four-, and six-engine bombers having a very low drag. The drag coefficient corresponds approximately to turbulent skin-friction drag, implying that pressure drags have been eliminated. Although airplane models have been tested giving drags as low as those assumed for these airplanes, no bombers have as yet been built which can demonstrate this low drag in flight. A serious impédence to the development of a bomber with a low parasite drag is the ever present and perhaps increasing need for powerful defensive armament.

The reduction of pressure drags to a minimum probably means that all turrets would have to be retractable and great perfection attained in the general aerodynamic design.

PERFORMANCE TRENDS

Range

Comparison of the bombers with one, two, four, and six engines and a drag coefficient, $C_{D_o} = 0.0120 + 0.12\ F/S$, are made at a take-off distance of 4000 feet. For a given power loading the wing loading is selected to give this take-off distance and is the same for each type, so that in reality the comparison is also made at constant power loading and constant wing loading.

Figure 2(a) gives the maximum range of bombers with a drag coefficient, $C_{D_o} = 0.0120 + 0.12\ F/S$, a 4000-foot take-off distance, and a bomb load of 10,000 pounds. At a power loading of 25, the four- and six-engine bombers are equal. At a power loading of 10, the range of the four-engine bomber is about 90 percent that of the six-engine bomber. The two-engine-bomber ranges are always the smallest over the power loadings investigated. At the highest power loading, the range is 90 percent as great as the range of the four- and six-engine bombers.

A large gain in range may be obtained by increasing the power loading from 10 to 15, a substantial gain from 15 to 20, and but a small gain from 20 to 25.

A comparison of bombers of different power and weight, all with the same bomb load, gives an advantage to the larger airplanes. Figure 2(b) is the same as 2(a) except that the maximum range for no bomb load is given. The trends shown for no bomb load are about the same as would be obtained for bomb loads proportioned according to the relative weight and power of the different types.

Figure 2(b) shows little difference between the ranges of the two-, four-, and six-engine bombers at power loadings of 20 and 25, and little difference between the four- and six-engine bombers at lower power loadings.

Speed

Figure 2(c) gives the high speed of bombers with two, four, and six 3000-horsepower engines, a drag coefficient, $C_{D_0} = 0.0120 + 0.12\ F/S$, and with a take-off run of 4000 feet. The speeds of the two-engine bombers are about 90 percent of that of the six-engine bombers, while the speeds of the four-engine bombers are just slightly less than the speed of the six-engine bombers.

A more impressive difference in speed is observed at different power loadings. Increases of high speed averaging about 70 miles per hour are indicated for each 5-pound-per-horsepower decrease in power loading.

Rate of Climb

The rate of climb increases very slightly with an increase in the number of power plants (fig. 2(d)).

Parameters Affecting Trends

The performance trend with number of engines is controlled by the effects of changes in scale. There are several advantages to increasing the size of the bombers. First, the fuselage surface area does not increase as fast as the weight of the airplane, and also there is the tendency for a greater degree of submergence of fuselage and nacelles in the wings of the larger airplanes, resulting in an increase in the L/D. Hence, the high speed, cruising speed, range, and rate of climb are all increased.

Further, there is always certain equipment the weight of which does not increase as rapidly as the gross weight and hence is a smaller proportion of the weight of the larger bomber. On the other hand, there is a strong tendency for the percentage of structural weight to increase with scale. In very large sizes, the latter factor controls and a smaller proportion of disposable load results. Hence, it is possible for the range of a four-engine bomber to exceed that of a six-engine bomber at high power loadings.

Performance Available

By an examination of the selection charts, the maximum range which can be obtained by a given family of bombers having any desired high speed may be obtained. Tables have been prepared giving this information for several high speeds (at 35,000 ft) for bombers carrying a 10,000-pound bomb load. Tables I, II, and III are for two-, four-, and six-engine bombers having drags comparable to those of present-day bombers.

TABLE I

TWO-ENGINE BOMBER

$$\left[C_{D_o} = 0.0120 + 0.12\ F/S\right]$$

Speed (mph)	Range (miles)	Take-off run (ft)	Climb (ft/min)	Power loading	Wing loading
250	7300	3500	500	24.0	42
300	6800	3400	750	19.4	47
350	5600	3500	1000	15.2	60

TABLE II

FOUR-ENGINE BOMBER

$$\left[C_{D_o} = 0.0120 + 0.12\ F/S\right]$$

Speed (mph)	Range (miles)	Take-off run (ft)	Climb (ft/min)	Power loading	Wing loading
300	8300	4000	625	20.4	53
350	7750	4000	800	16.8	62
400	6800	4000	1300	13.1	74

TABLE III

SIX-ENGINE BOMBER

$$\left[C_{D_o} = 0.0120 + 0.12\ F/S\right]$$

Speed (mph)	Range (miles	Take-off run (ft)	Climb (ft/min)	Power loading	Wing loading
300	8550	4500	600	20.2	60
350	8200	4500	775	17.2	66
400	7300	4500	1000	14.0	77

Better performance could be obtained with bombers with a reduced drag. However, the need for strong defensive armament is a factor tending to make the reduction of drag difficult.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 13, 1942.

APPENDIX

The appendix is a discussion of the various parameters, such as drags and weights, used in the construction of the performance charts.

Power Plants

The bombers are all powered by 3000-horsepower engines. It is assumed that each nacelle requires a projected frontal area of 25 square feet for housing and the admission of cooling air. Weight estimates are made to include all auxiliary equipment necessary for full power operation to 35,000 feet. The curve of minimum specific fuel consumption used in this analysis is given in figure 9.

Drags

Two sets of drag coefficients are used to represent two degrees of aerodynamic excellence. One is used to represent airplanes about equal to the best which have been built at the present time. By exercising care in design it should be possible to build airplanes with performances equal to those of this group with a reasonable degree of certainty. To represent this group, a wing and tail drag coefficient of 0.0120 based on wing area, and a fuselage and nacelle drag coefficient of 0.12 based on effective frontal area have been used. Thus, except for cooling, the minimum parasite drag coefficient for this case may be written $C_{D_0} = 0.0120 + 0.12\ F/S$ where F represents the effective frontal area of the fuselage plus nacelles and S, the wing area.

In order to obtain an extremely high-performance bomber, the parasite resistance must be cut down to approach the skin-friction drag of a fairly smooth surface. A wing and tail drag coefficient of 0.0090 and a fuselage and nacelle drag coefficient of 0.06 based on effective frontal area are used to represent this condition. Thus, the drag coefficient for this case is $C_{D_0} = 0.0090 + 0.06\ F/S$. Although drag coefficients this low have been obtained in wind-tunnel tests, they have not been demonstrated by bombers in actual flight. These low drags must therefore be considered to represent future airplanes of advanced design, with retractable turrets, etc. The amount of time necessary to develop such an airplane is, of course, highly problematical.

The effective frontal area is the actual frontal area less an allowance made because the fuselage and nacelles are not complete bodies but are partially submerged in the wing. The fuselage area for a given family of bombers is taken to vary with the two-thirds power of the gross weight. The values of effective fuselage, nacelle, and total effective frontal areas for the several families of bombers are given in figure 10. Of two bombers with the same gross weight and different number of engines, the bomber with the larger number of engines has the smaller fuselage since more of the weight is in the nacelles.

Span Factor

An addition to the parasite and ideal induced drag with increasing lift coefficient is assumed and expressed as an increase in the induced drag. Thus, the induced drag is divided by a "span factor" as in the equation

$$D = C_{D_0}qS + \frac{\left(\frac{W}{b}\right)^2}{eq}$$

The value of e is taken as 0.8 in this analysis.

Propeller Efficiency

It was assumed that a propeller efficiency of 85 percent could be realized. In order to simplify the performance computations, it is assumed that cooling power is proportional to brake power. This assumption makes it possible to take account of the cooling losses by an equivalent reduction of the propeller efficiency. Five percent of the brake power was allowed for cooling for sea-level operation, giving an effective propeller efficiency of 80 percent. This value was used for the range and rate-of-climb calculations. At 35,000 feet altitude, the cooling power will be greater and was assumed to be 10 percent of the brake horsepower giving an effective propeller efficiency of 75 percent for the high-speed computations.

Aspect Ratio

An aspect ratio of 12 has been used throughout for each type. Figures 7(a), 7(b), and 7(c) show the effect of aspect ratio on the maximum range of three families of bombers for wing loadings of 40 and 60. There is evidently considerable variation in the optimum aspect ratio. For the higher wing loadings, induced drag is more important and a higher aspect ratio is optimum. Also, there is a small variation of the optimum between the two-, four-, and six-engine bombers. The unit wing weight is higher for the larger bombers and, at a given wing loading, makes a smaller aspect ratio optimum. Because of the flat nature of the curves and because other performances are also affected to some extent by aspect ratio, the same value has been used throughout.

Load Factor

A design load factor of 4 with the 10,000-pound bomb load has been used over the entire chart. This is sufficient to protect against a standard gust of 30 feet per second except for extremely light wing loadings. Very modest maneuverability is afforded by this load factor.

Wing Thickness

A 20-percent wing-thickness ratio at the root chord was used for all the airplanes. This wing is thick enough to keep the wing weight reasonable but not thick enough to cause a high drag or to experience compressibility at maximum speed. It is quite likely that the optimum wing thickness is considerably higher than the 20 percent used in this computation.

Weight

After a study of Air Forces airplanes, it was assumed that:

1. Fuselage weight is 8 percent of airplane gross weight.

2. Landing-gear weight is 6 percent of airplane gross weight.

3. Tail weight is 10 percent of wing weight.

4. Certain weights which vary with the gross weight are given in the following table.

Weight Table

Gross weight	Fixed equipment	Fuselage (0.08W)	Landing gear (0.06W)
50,000	6,000	4,000	3,000
100,000	8,000	8,000	6,000
200,000	12,000	16,000	12,000
300,000	15,800	24,000	18,000
400,000	18,300	32,000	24,000
450,000	19,000	36,000	27,000

5. Each power plant including accessories weighs 6750 pounds.

6. Weight of fuel system equals 0.55 pound per gallon of gasoline.

7. Weight of lubricating system equals 1.25 pounds per gallon of oil.

Sufficient tankage weight is included to obtain maximum range with no bomb load. The tanks are assumed to be carried in the wings.

Wing Weight

Wing weight is determined by considerations of strength. An expression equating the internal resisting moment to the external bending moment at the center section gives the following relationship:

$$K = \frac{W - (C_1W_2 + W_1)}{W_1} \times \frac{fR^{\frac{3}{2}} S^{\frac{1}{2}}}{t}$$

where K is a coefficient dependent upon:

1. The distribution of lift along the span
2. The strength weight ratio of the material used in the construction of the wing
3. The perfection of the design as an efficient weight to strength beam. The higher the K, the more efficient the beam as a weight-carrying structure.

For simple loading conditions, such as those for pursuit airplanes where nearly all of the load is concentrated in the fuselage, it is to be expected that a value of $C_1 = 0$ would approximate the loading condition. For multiengine bombers, where a large portion of the load is distributed along the wing, a value of C_1 between 0.5 and unity would be expected to approximate the loading condition. For the purpose of this analysis, a value of $K = 100{,}000$ and a value of $C_1 = 0.85$ were used on the basis of the study of existing airplanes. To solve this equation for wing weight, if the value of the load to be carried in the wings is as yet unknown, W_2 may be conveniently expressed as the gross weight less the weight of the fuselage and the weight carried by the fuselage (including the tail surfaces) less the wing weight.

Take-Off Run

The take-off run is calculated assuming a level field and no wind and the take-off is executed at a lift coefficient of 1.3. Propeller efficiency is assumed to vary linearly from zero at the beginning of the run to 80 percent at 90 miles per hour and remain constant at 80 percent above 90 miles per hour. In order to simplify the calculations, rolling friction and air resistance during take-off are accounted for by assuming this resistance is equal to 10 percent of the propeller thrust. The distance to clear an obstacle is not included.

REFERENCES

1. Brevoort, Maurice J., Stickle, George W., and Hill, Paul R.: Generalized Selection Charts for Bombers with Four 2000-Horsepower Engines. NACA MR, May 11, 1942.

2. Brevoort, M. J., Stickle, G. W., and Hill, Paul R.: Generalized Selection Charts for Bombers Powered by One, Two, Four, and Six 2000-Horsepower Engines. NACA MR, July 6, 1942.

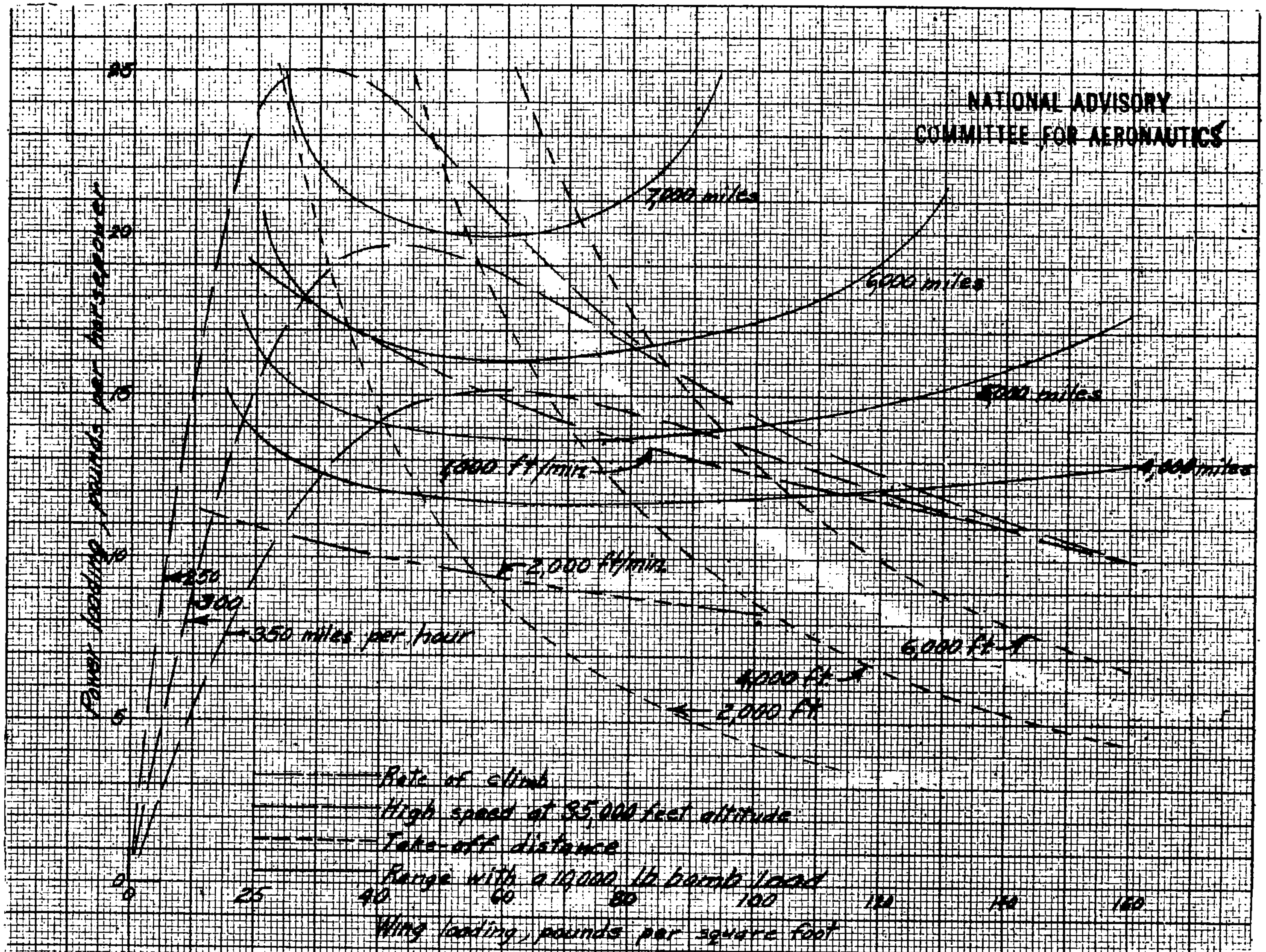

FIGURE 1a - PERFORMANCE SELECTION CHART FOR TWO-ENGINE BOMBERS, $C_{D_0} = .0120 + \frac{.12F}{S}$

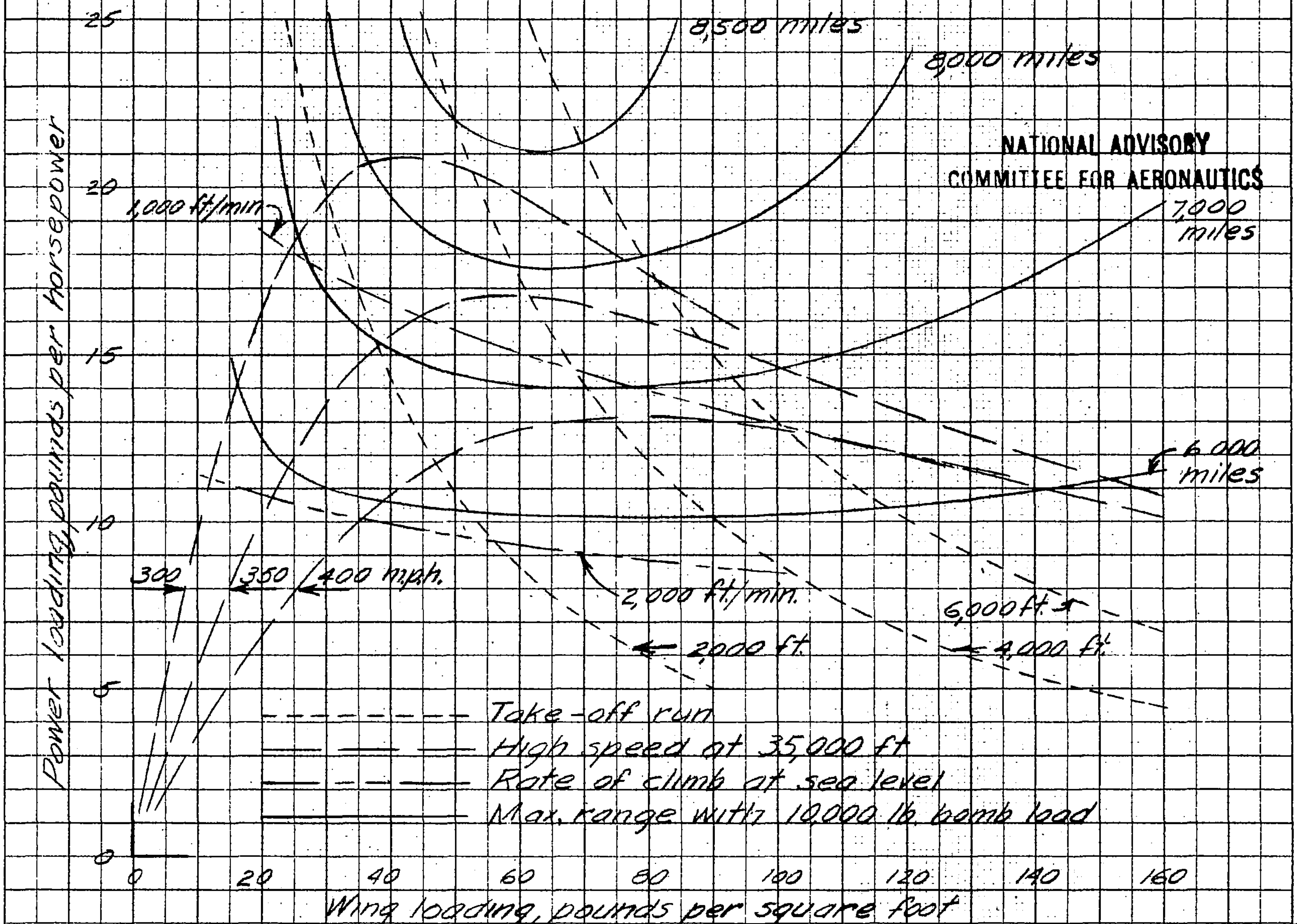

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Figure 1b – PERFORMANCE SELECTION CHART FOR FOUR-ENGINE BOMBERS. $C_{D_0} = .0120 + \frac{.12F}{S}$

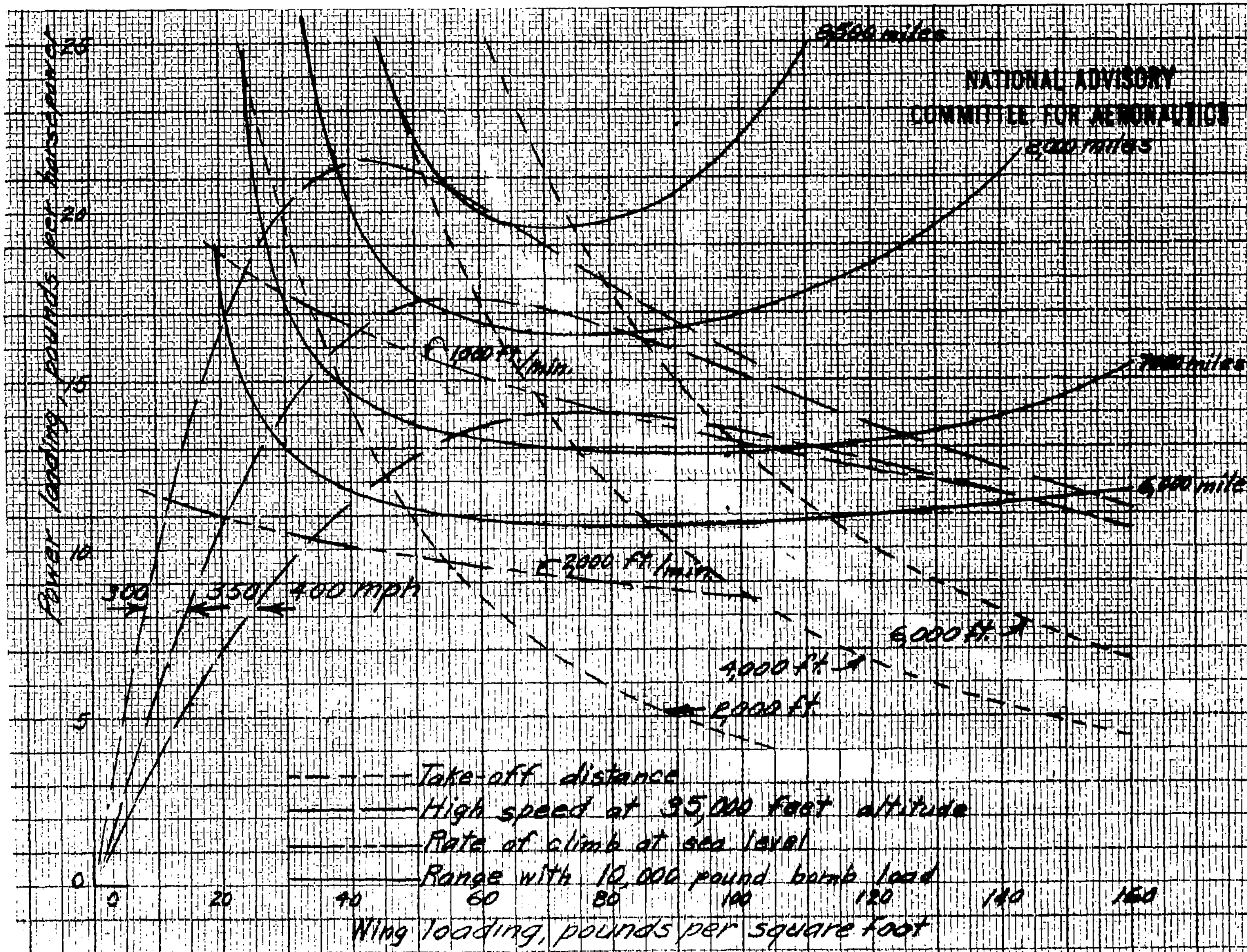

FIGURE 1C – PERFORMANCE SELECTION CHART FOR SIX-ENGINE BOMBERS, $C_{D_0} = .0120 + \frac{12.5}{S}$

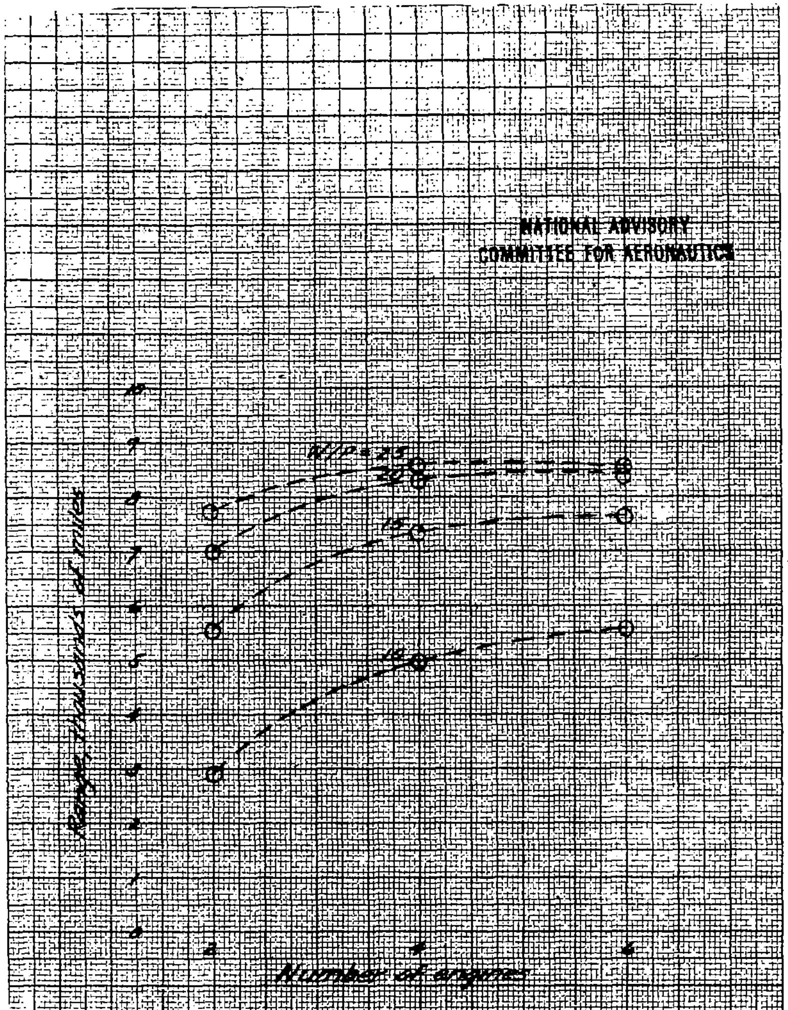

Figure 2a.- Effect of number of 3000 horsepower engines on maximum range of bombers with a take-off run of [illegible] ft. [illegible]

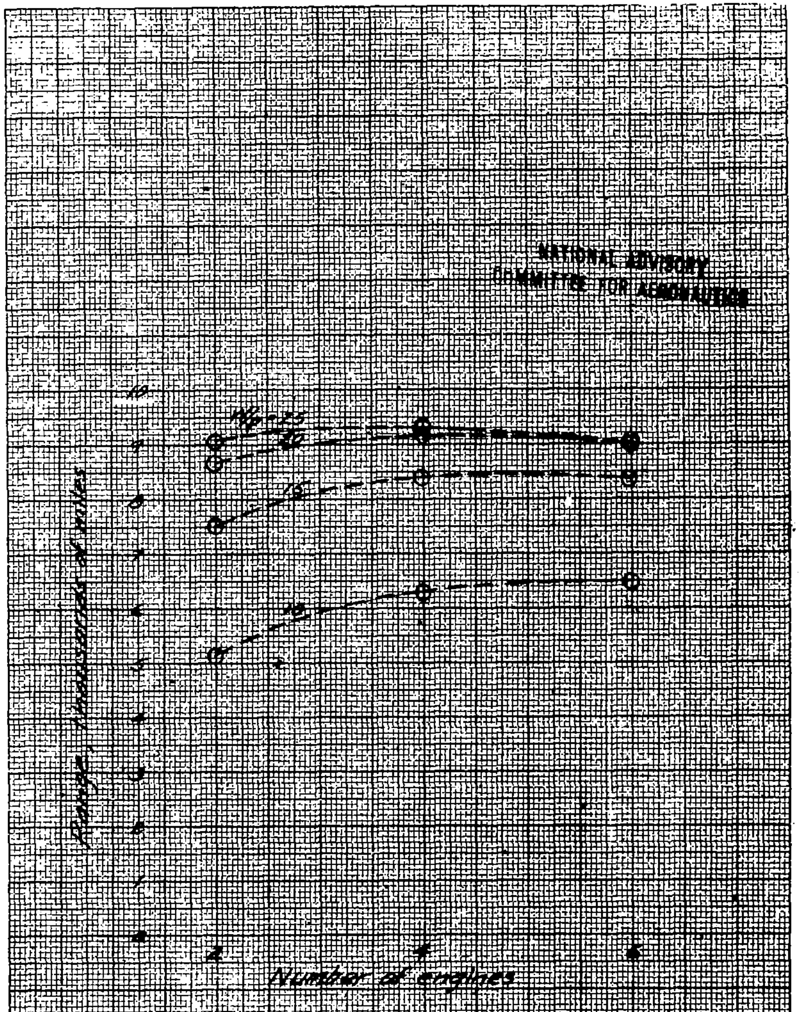

Figure 2b.- Effect of number of 3000 horsepower engines on maximum range of bombers with a take-off run of [illegible] feet. No bomb load. [illegible]

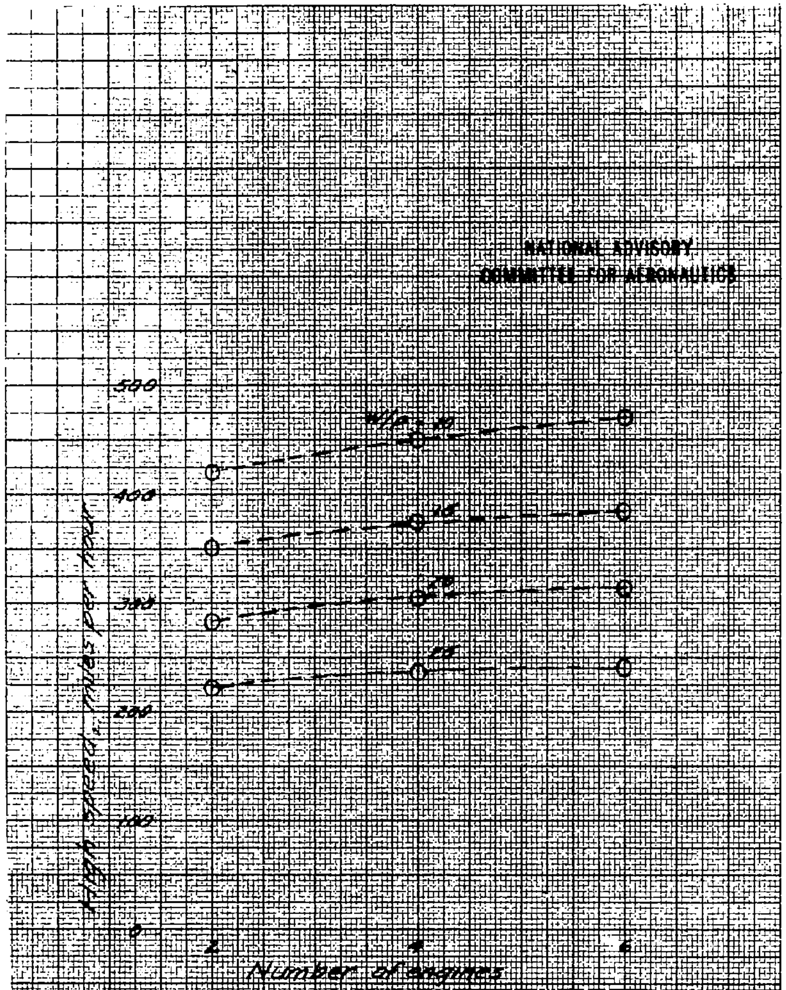

Figure 2C - Effect of number of 3000 horsepower engines on high speed at 35,000 ft. alt. of bombers with a take-off run of 4000 ft. $C_{D_0} = .0020 + .12\ F/S$

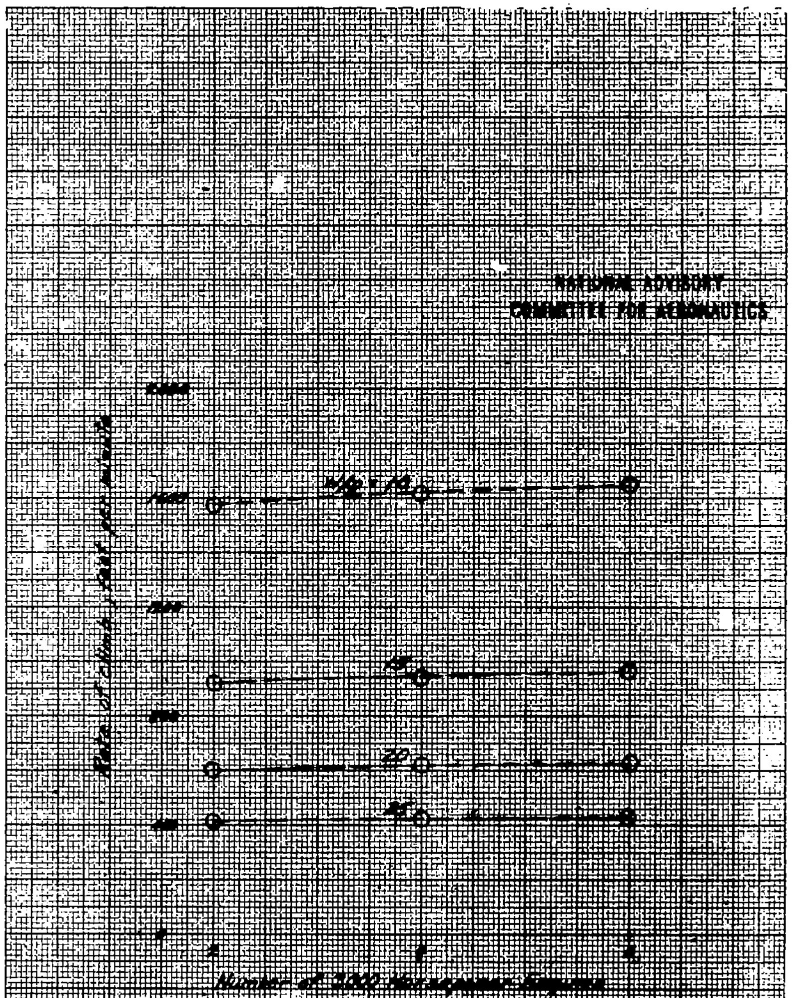

Figure 2D - Effect of number of 3000 horsepower engines on rate of climb of bombers with a take-off distance of 4000 feet. $C_{D_0} = .0020 + .12\ F/S$

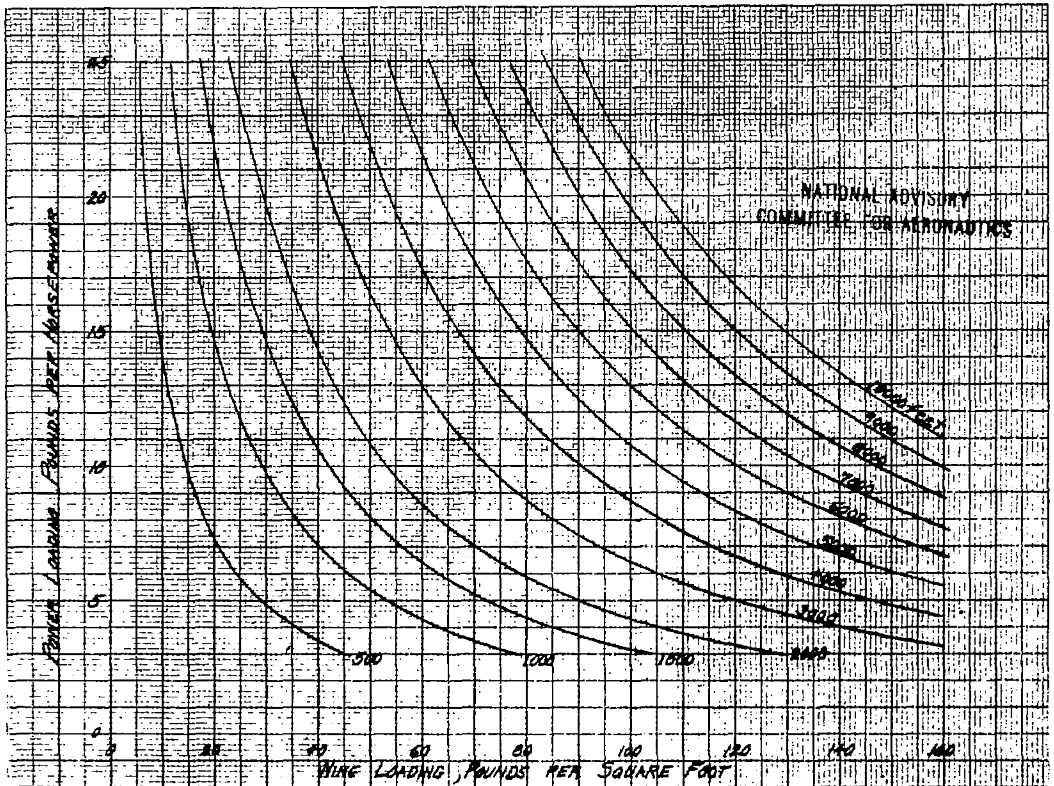

Figure 3 - Curves of Constant Take-off Run

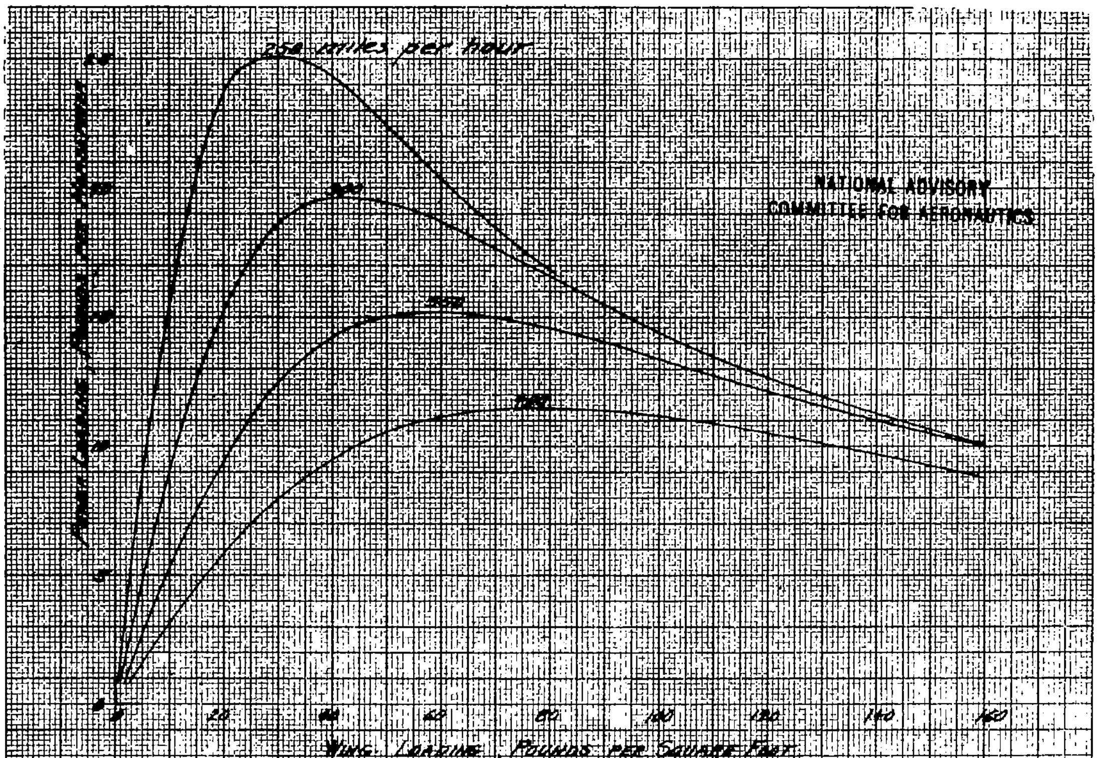

FIGURE 4a - HIGH SPEED OF TWO-ENGINE BOMBERS AT 35000 FEET. $C_{D_0} = .0120 + .12F/S$

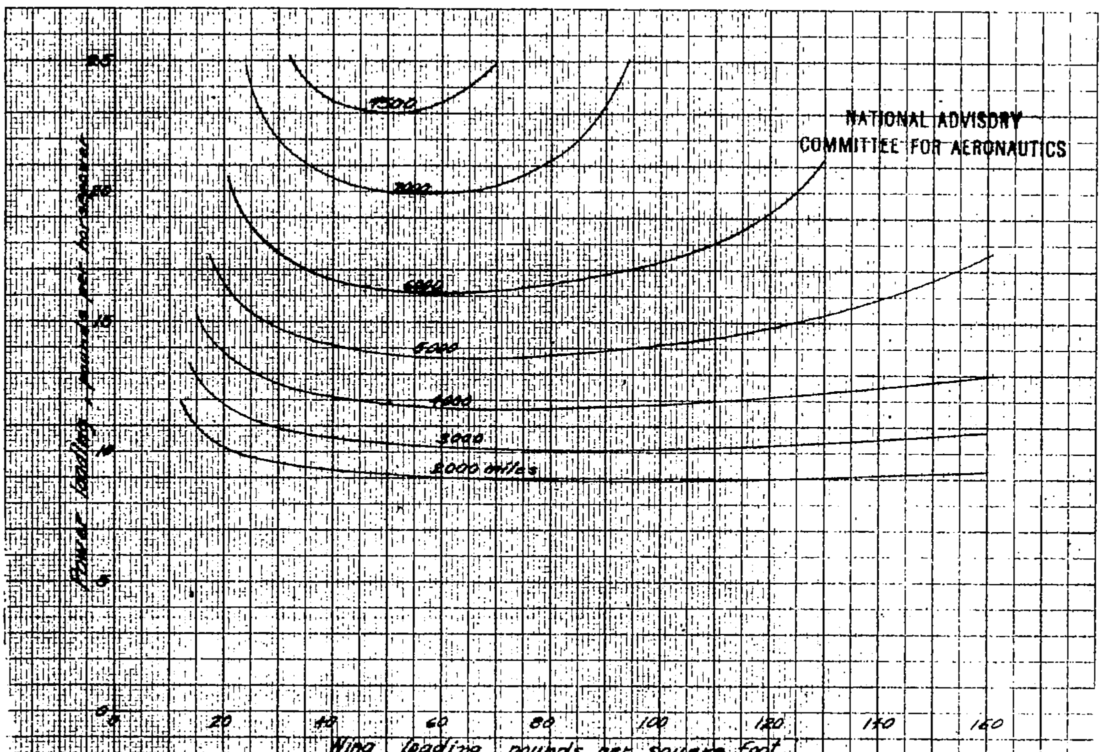

FIGURE 4b - MAXIMUM RANGE OF TWO-ENGINE BOMBERS WITH A 10,000 POUND BOMB LOAD $C_{D_0} = .0120 + \frac{.12F}{S}$

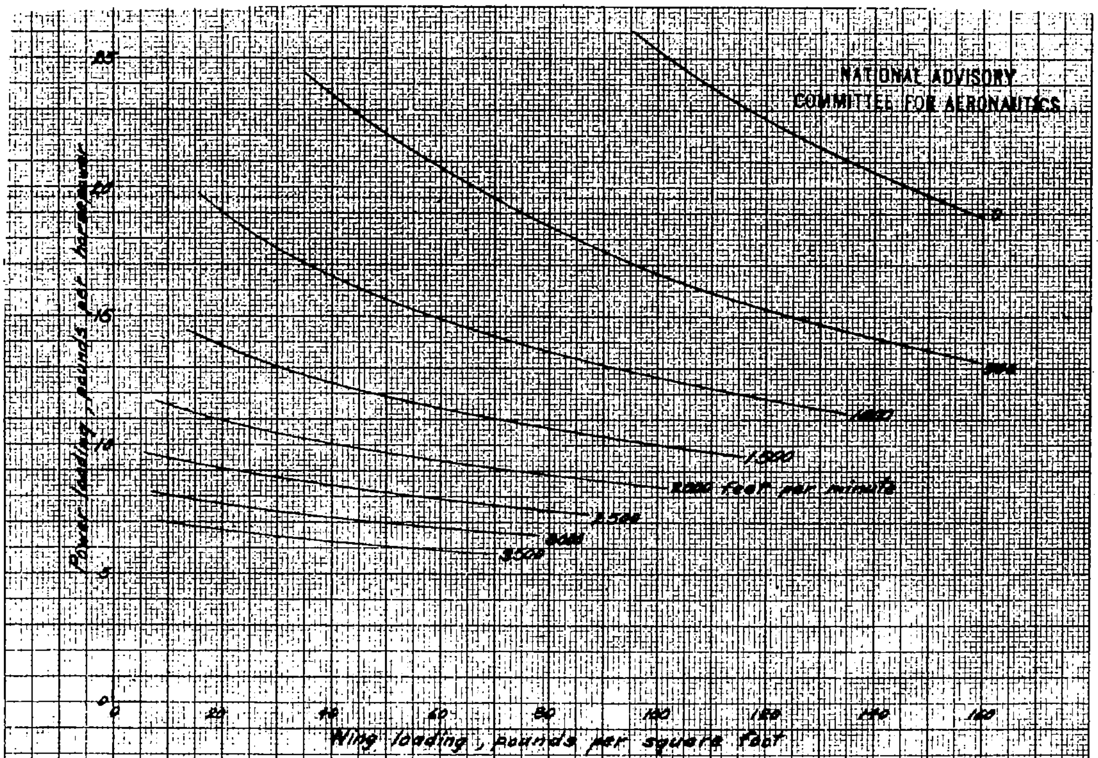

FIGURE 4c – RATE-OF-CLIMB OF TWO-ENGINE BOMBERS AT SEA LEVEL. $C_{D_0} = .0120 + .12\frac{F}{S}$

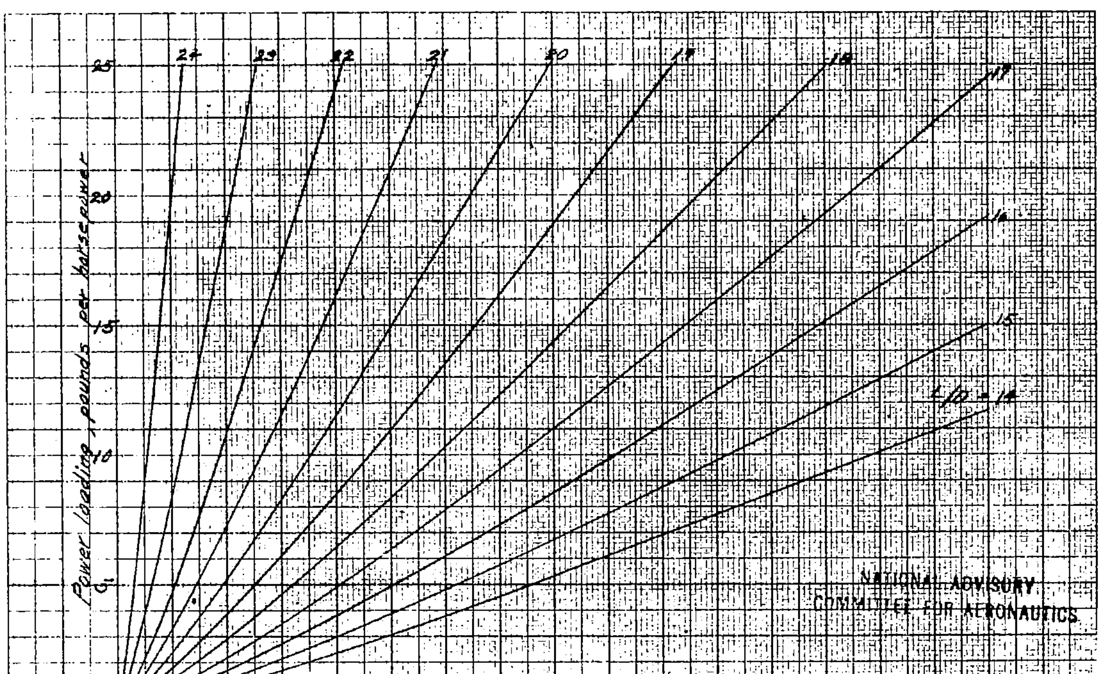

FIGURE 4d – MAXIMUM LIFT-TO-DRAG RATIO OF TWO-ENGINE BOMBERS. $C_{D_0} = .0120 + \frac{.12F}{S}$

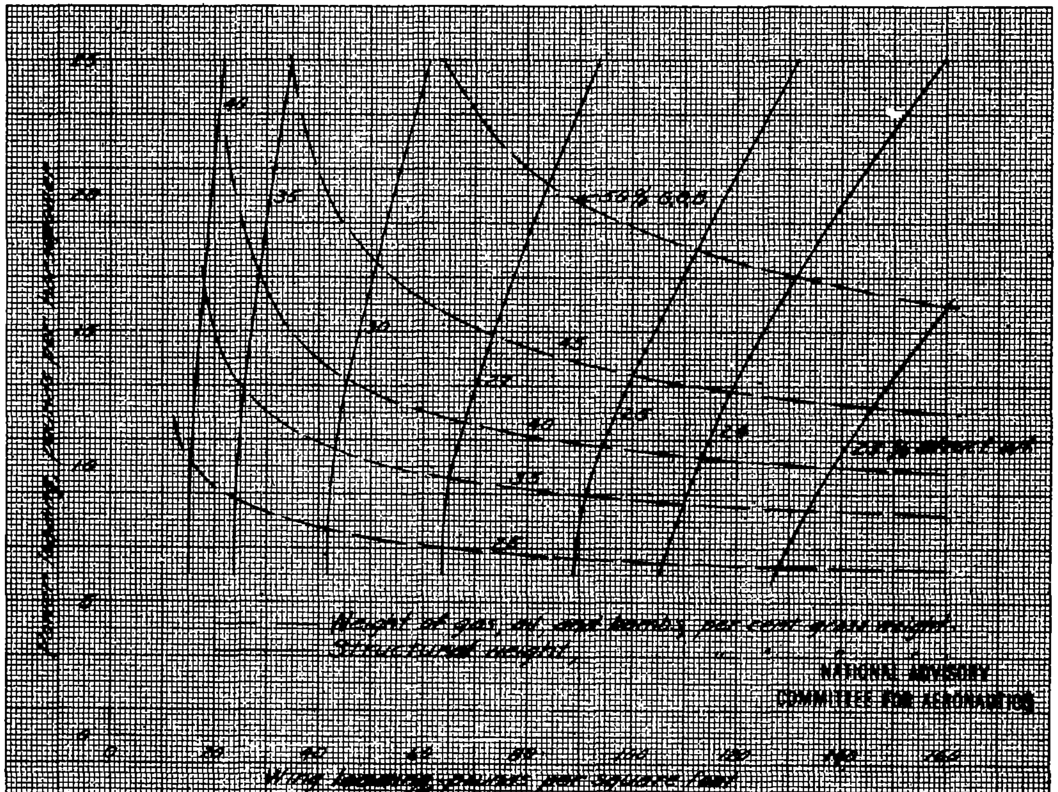

Figure 4a— Weight Chart for Two Engine Bombers

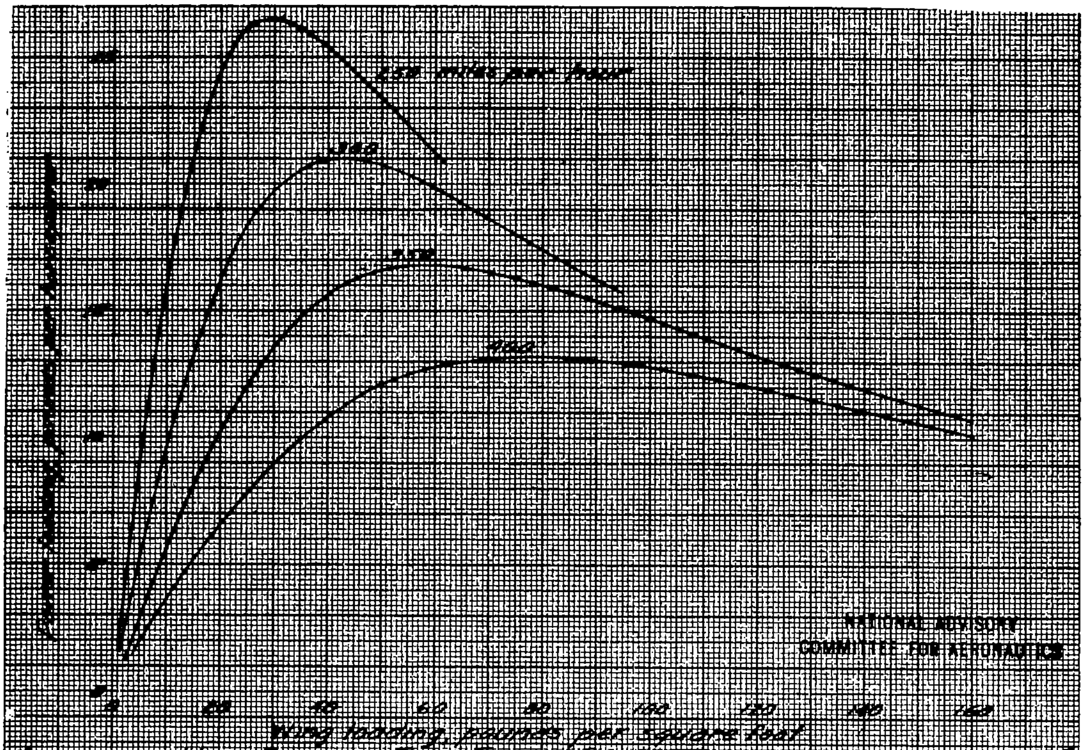

Figure 5a.- High speed of four-engine bombers at 35000 ft. C_{D_0} = [illegible]

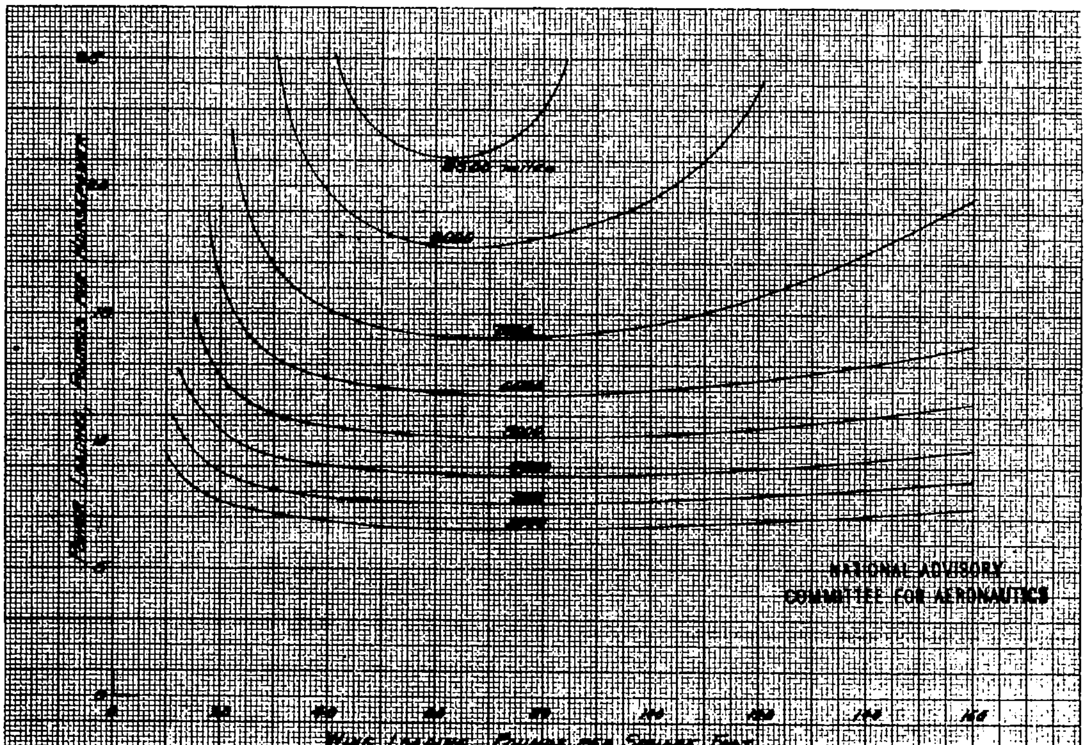

Figure 5b.- Max. range of four-engine bombers with 10,000 lb. bomb load C_{D_0} = .0120 + [illegible]

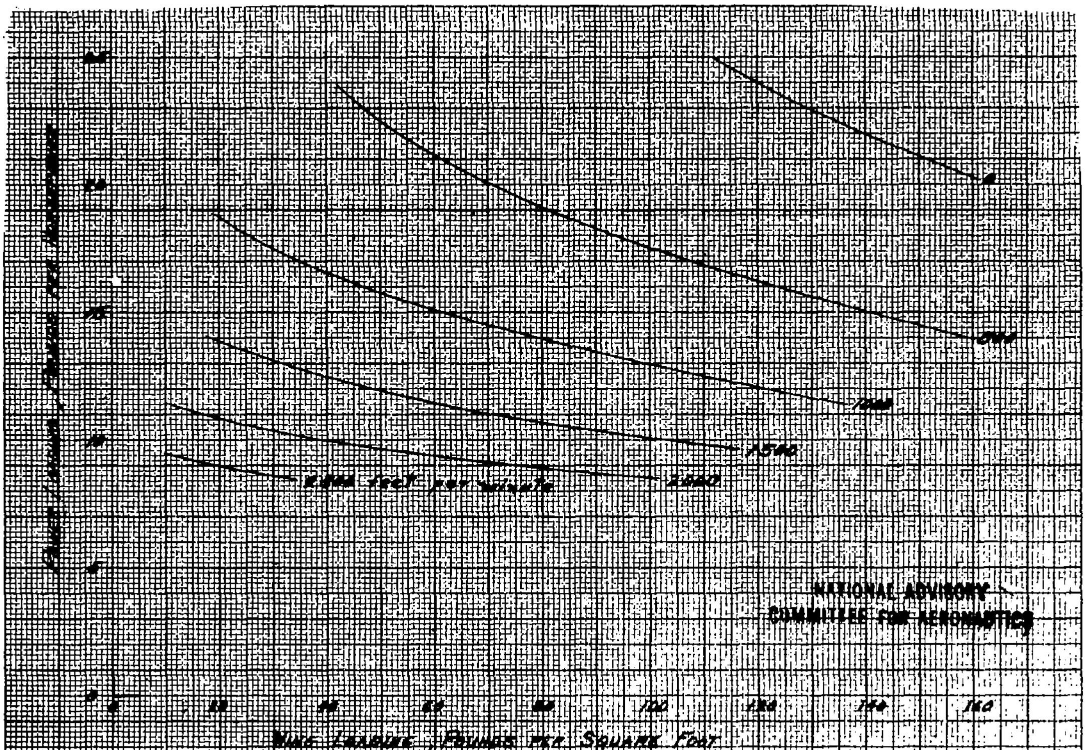

Figure 5c.- Rate of climb of four-engine bombers at sea level. $C_{D_0} = .0120 + .12F/S$

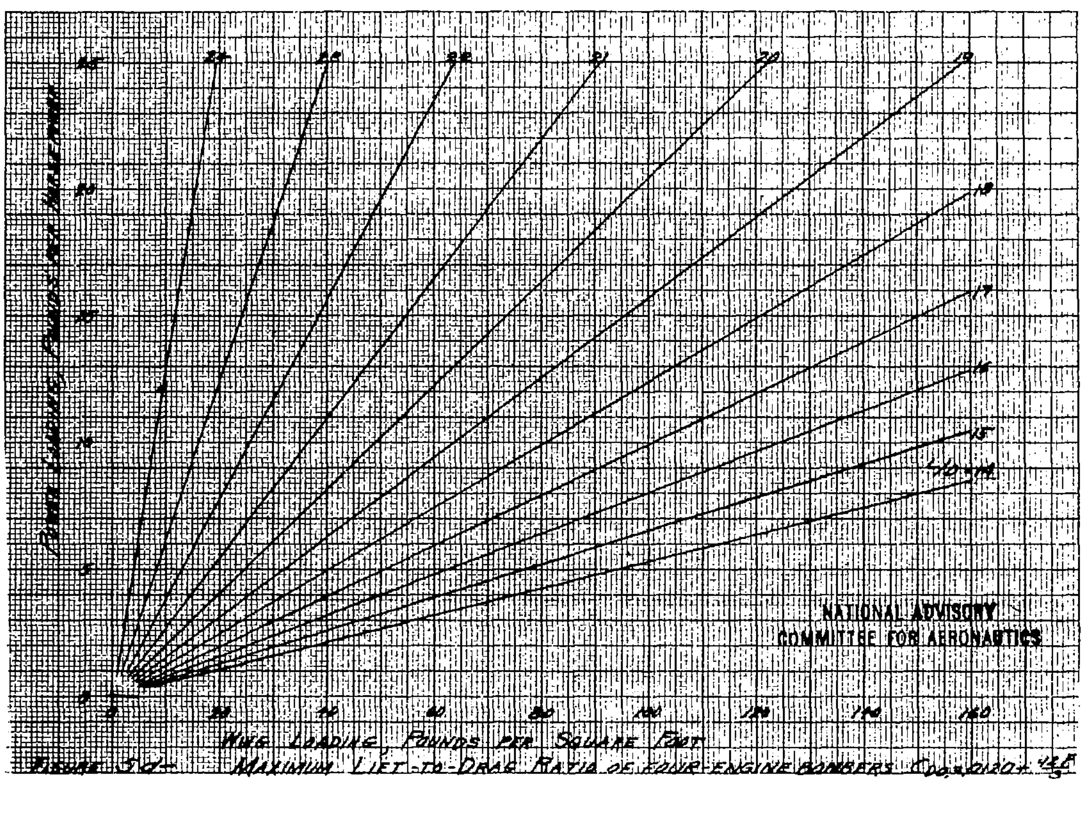

Figure 5d.- Maximum lift-to-drag ratio of four-engine bombers. $C_{D_0} = .0120 + \frac{.12F}{S}$

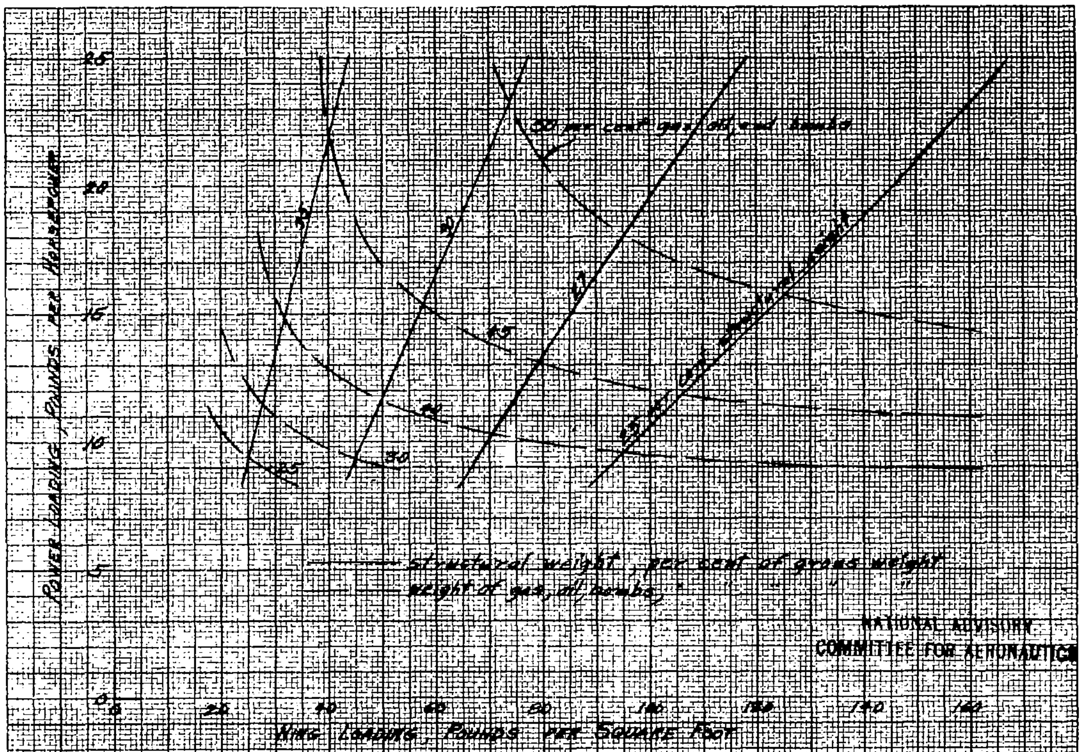

FIGURE 38 – WEIGHT CHART FOR FOUR-ENGINE BOMBERS

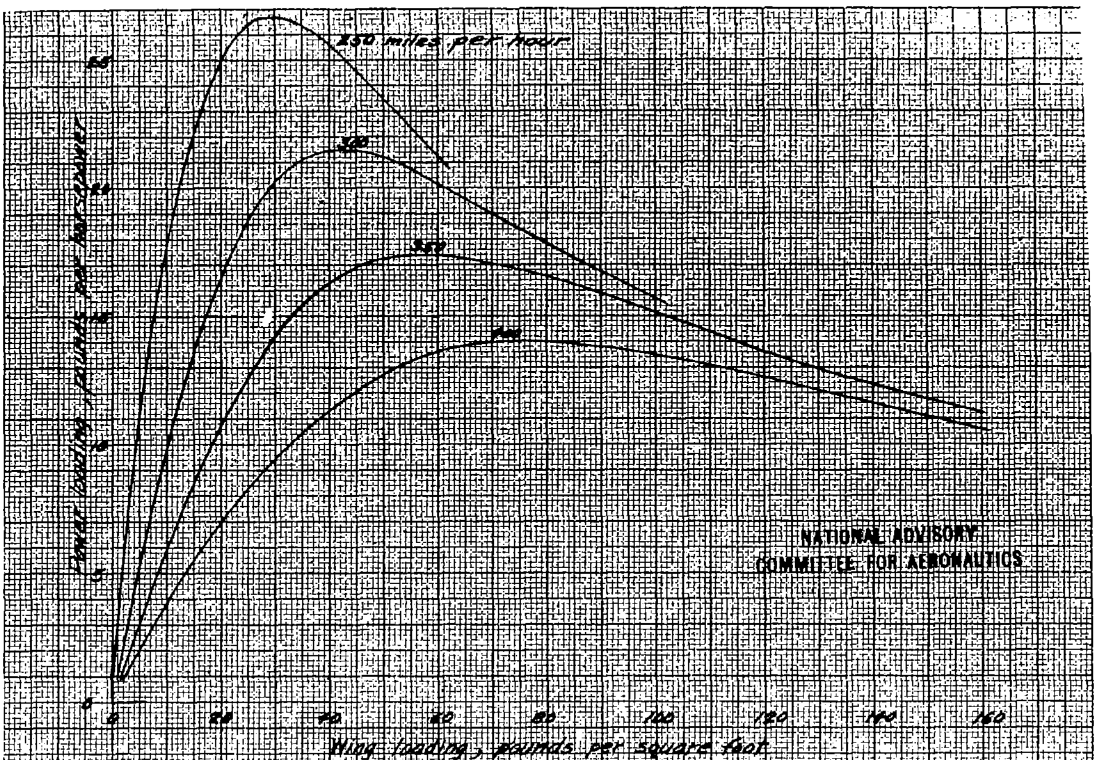

FIGURE 6a – HIGH SPEED OF SIX-ENGINE BOMBERS AT 35,000 FEET; C_{D_0} = .0120 + .12 F/S

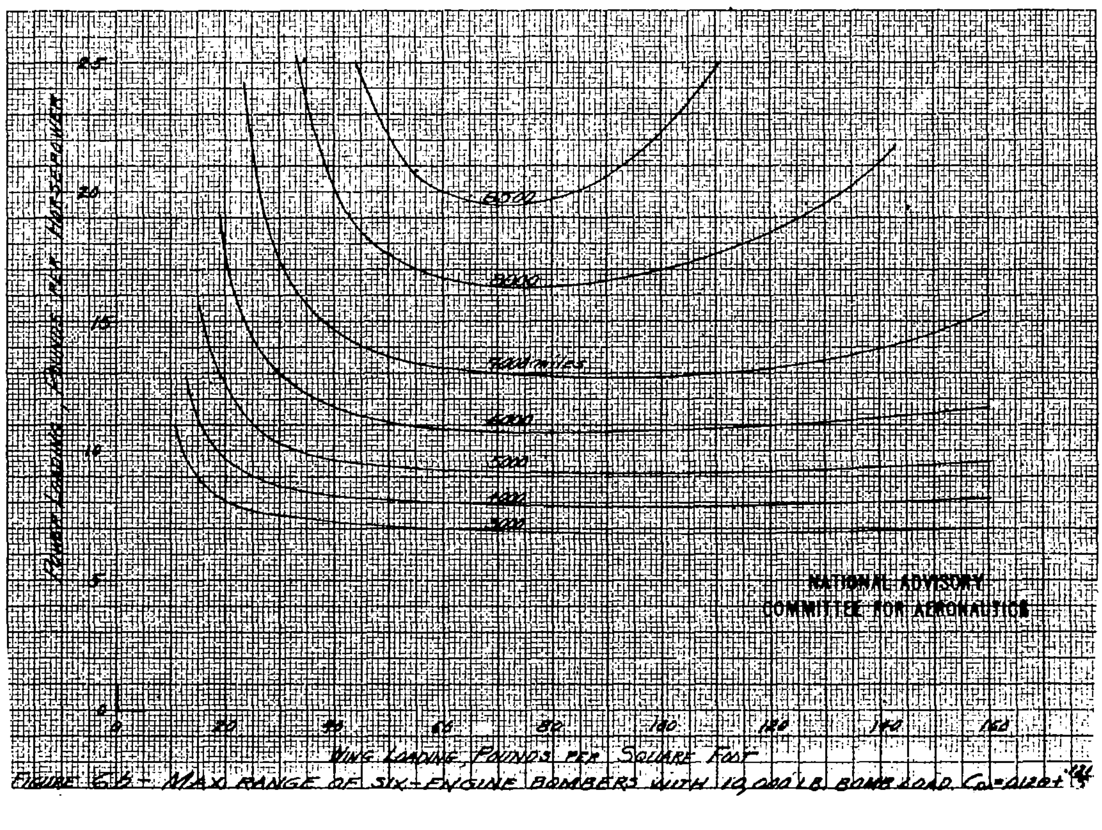

FIGURE 6b – MAX RANGE OF SIX-ENGINE BOMBERS WITH 10,000 LB. BOMB LOAD. C_{D_0}=.0120+ .12F/S

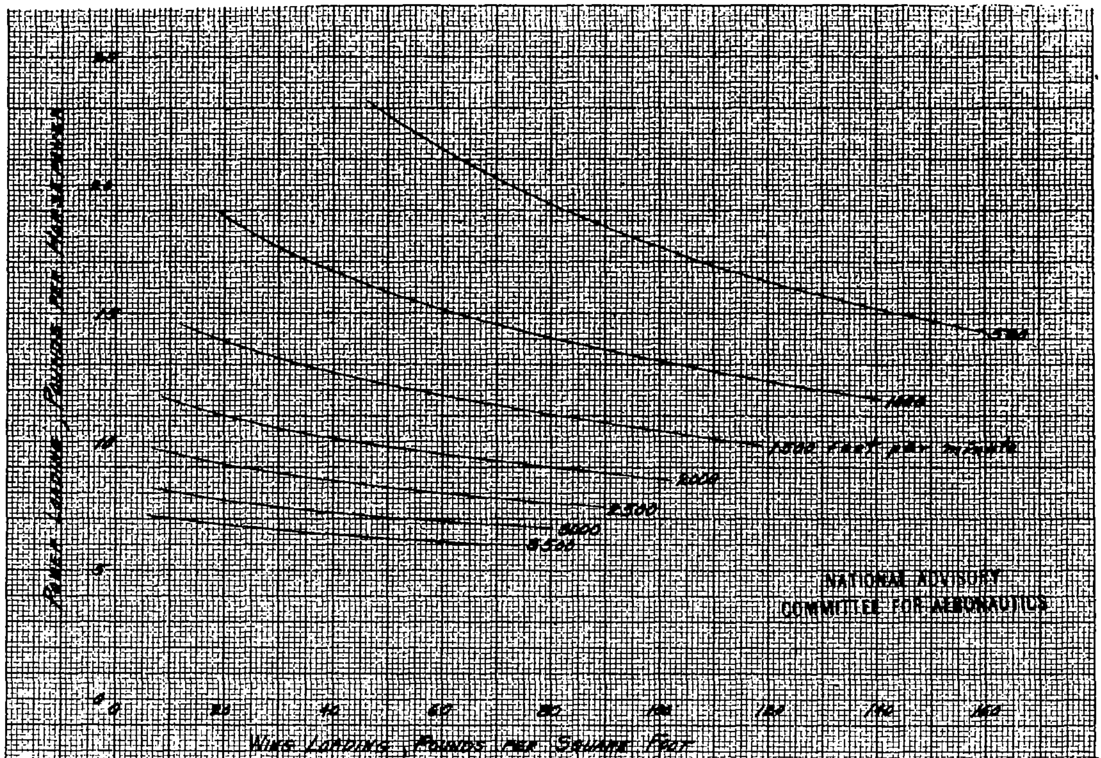

FIGURE 6c – RATE OF CLIMB OF SIX ENGINE BOMBERS AT SEA LEVEL. $C_{D_0} = .0130 + \frac{.14F}{S}$

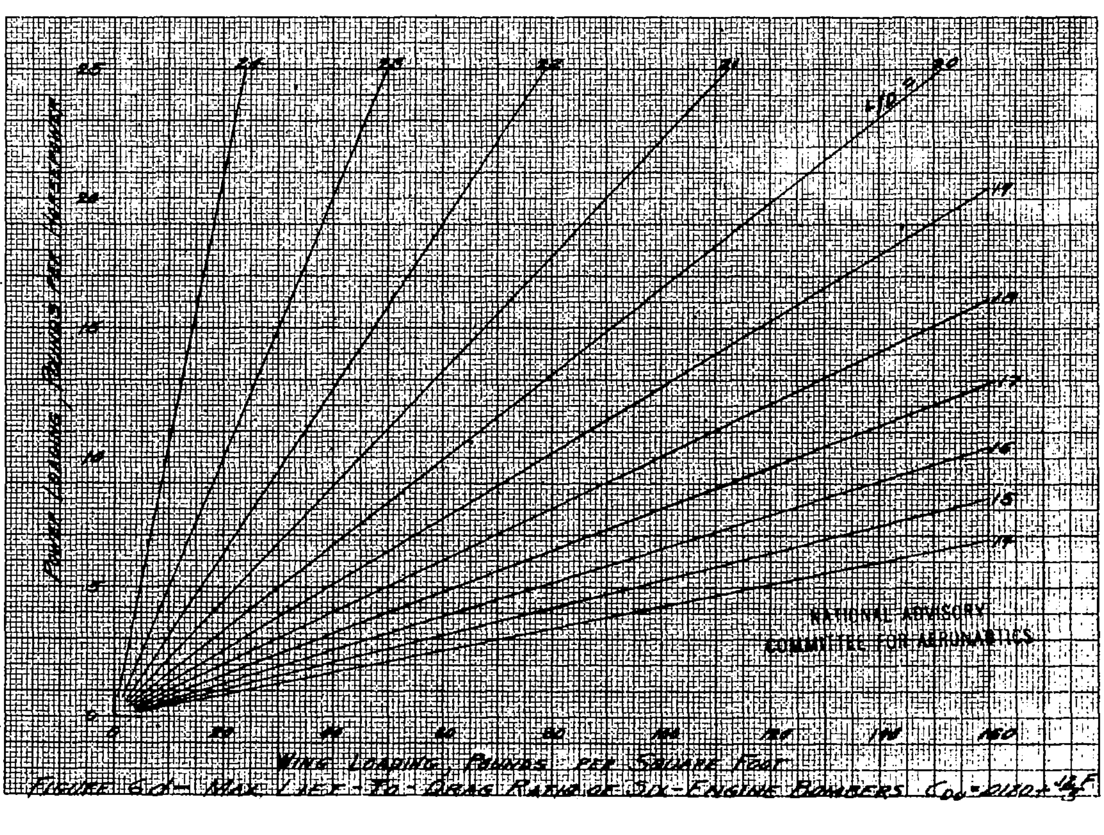

FIGURE 6d – MAX. LIFT-TO-DRAG RATIO OF SIX-ENGINE BOMBERS $C_{D_0} = .0130 + \frac{.14F}{S}$

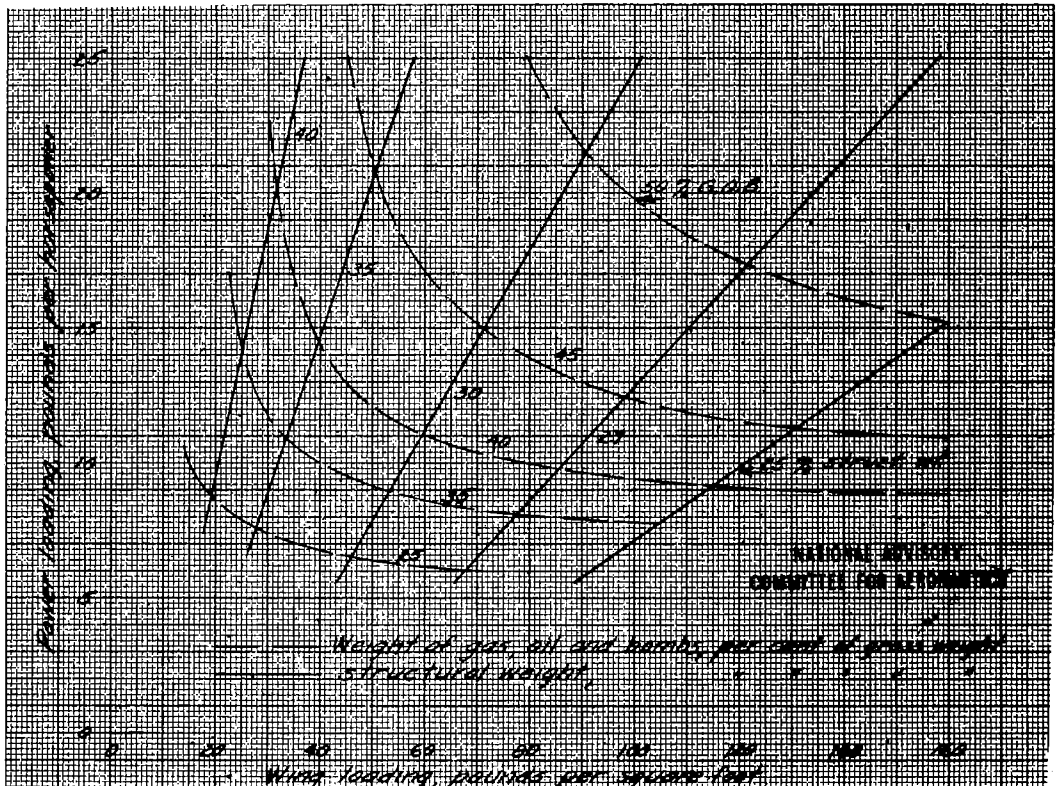

FIGURE 66.- WEIGHT CHART FOR SIX-ENGINE BOMBERS

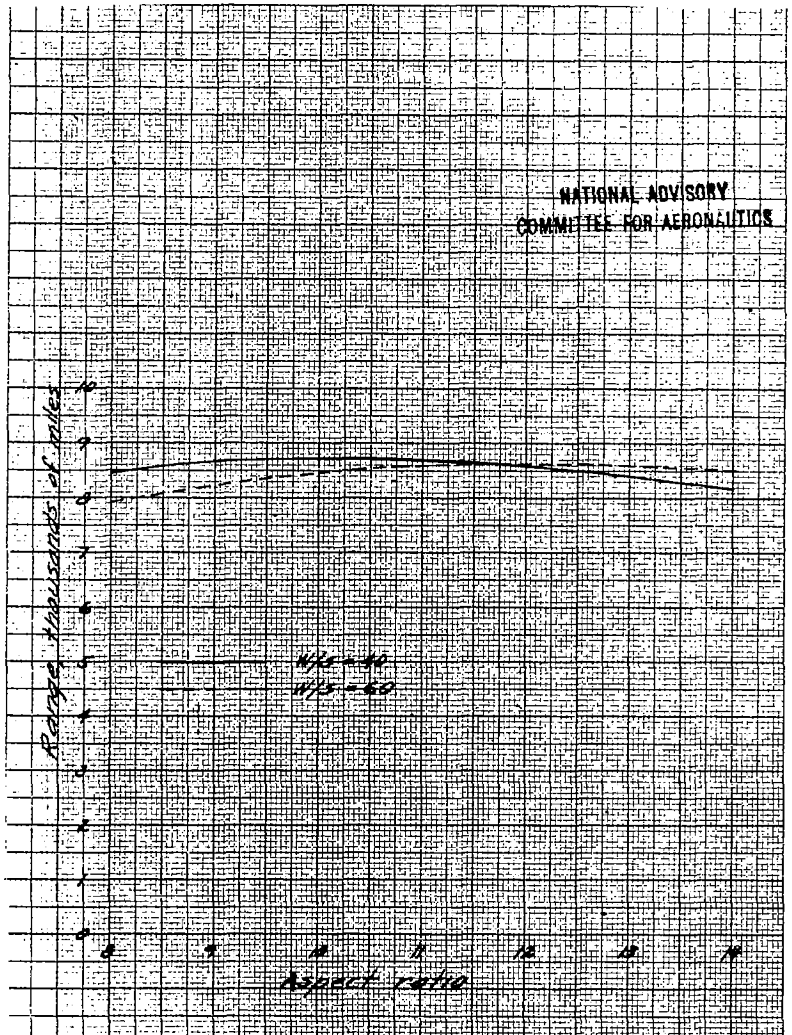

Figure 7a - Effect of aspect ratio on range of two-engine bombers. W/R=20 C_{D_0}=.0120+.12F/S

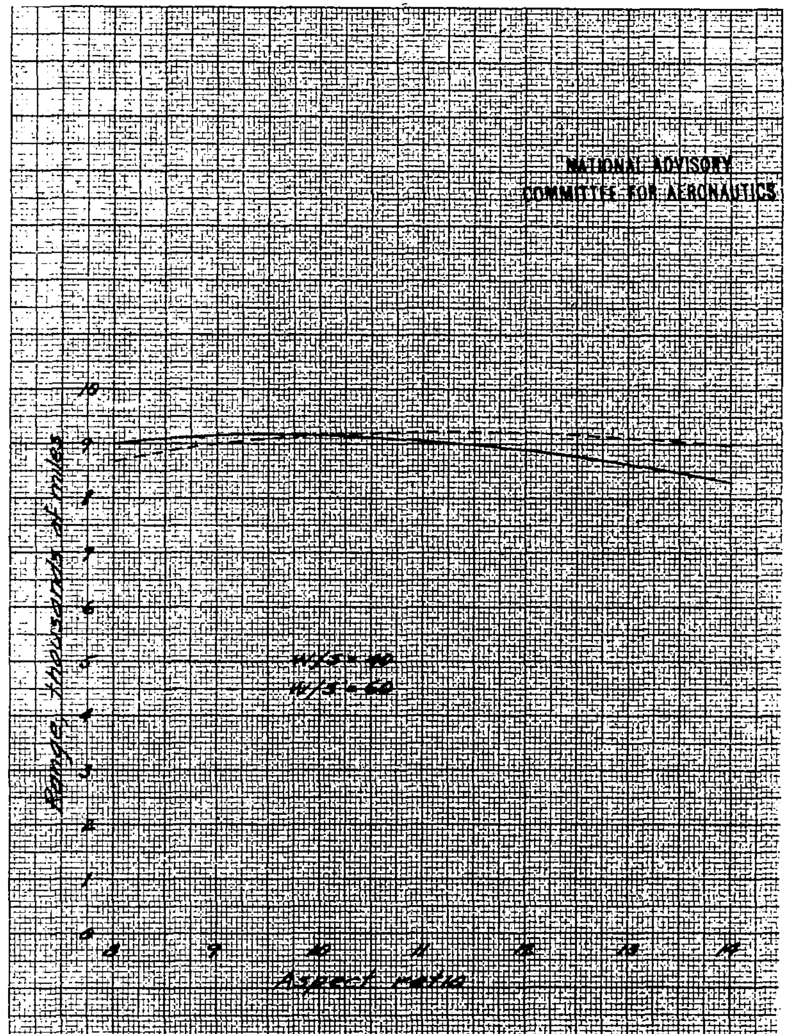

Figure 7b - Effect of aspect ratio on range of four-engine bombers. W/R=20 C_{D_0}=.0120+.12F/S

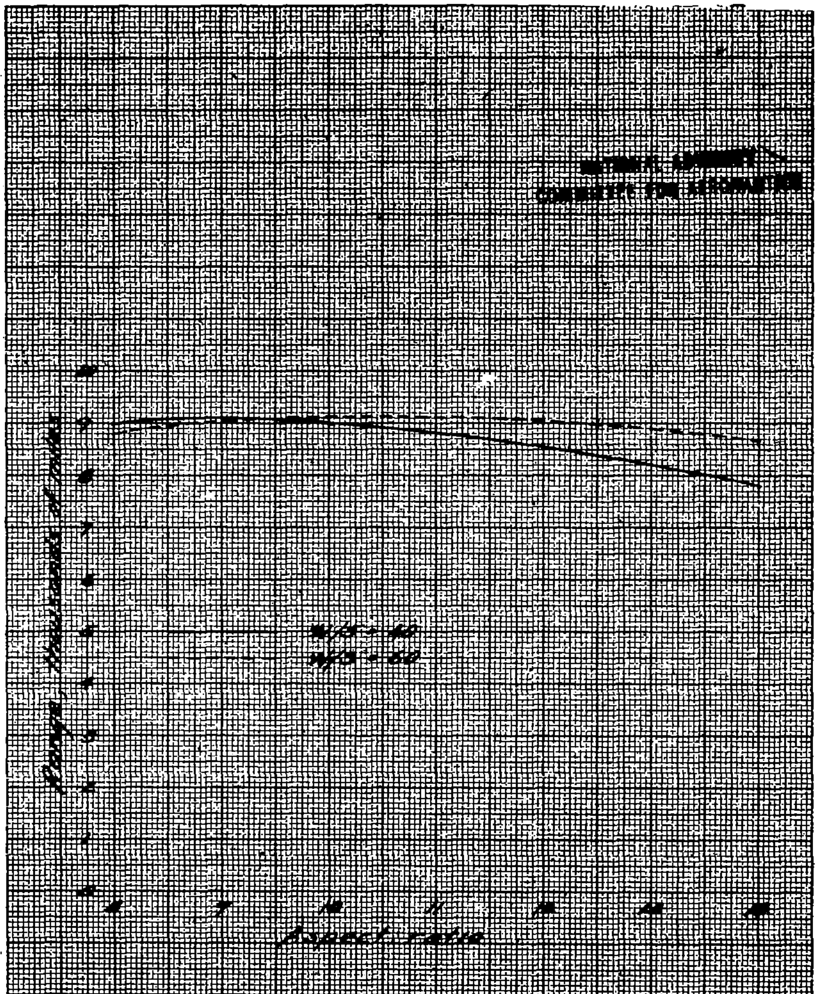

Figure 70.- Effect of aspect ratio on range of six-engine bombers.

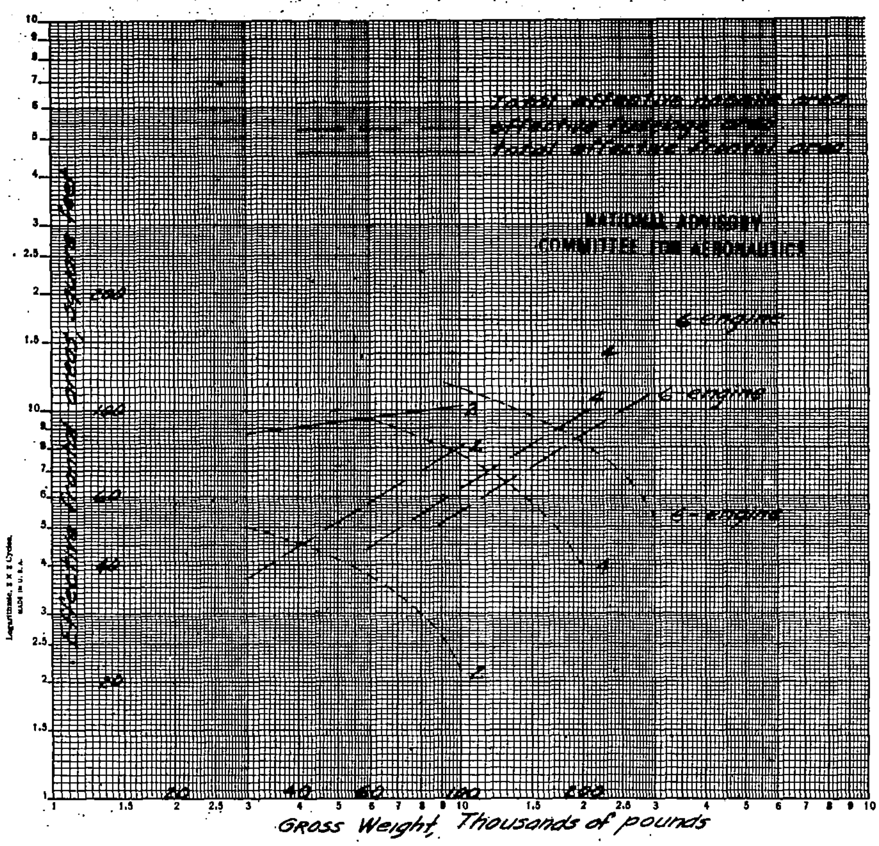

Figure 8 - Effective Fuselage and Nacelle Frontal Areas.

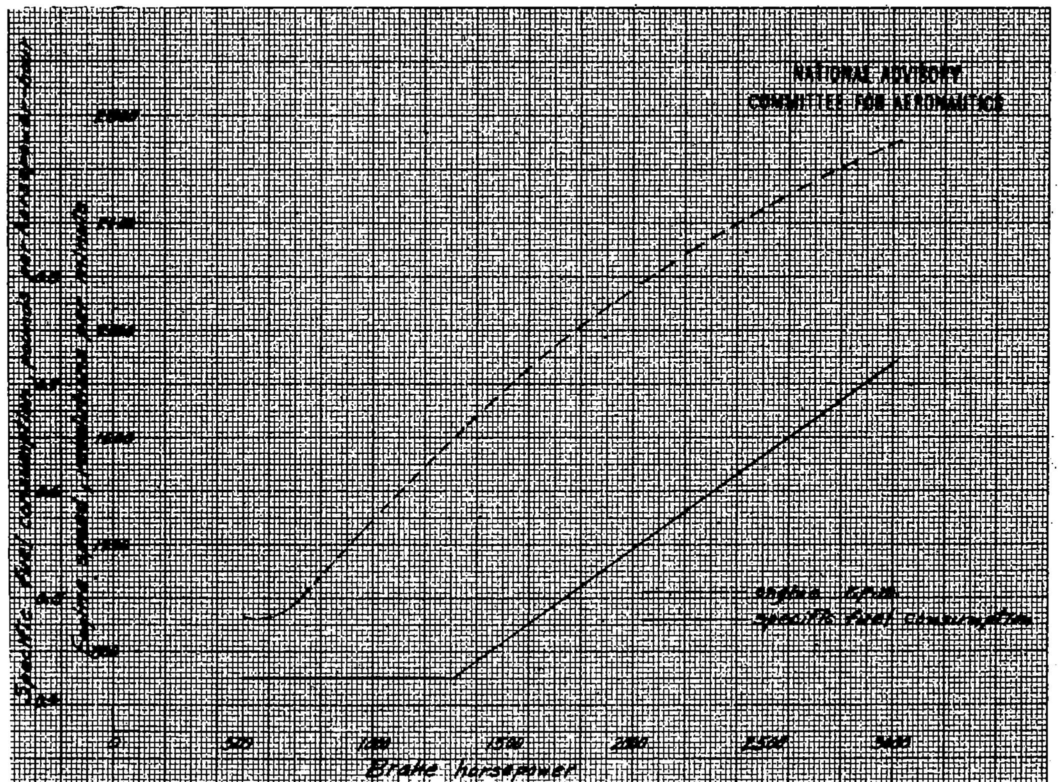

Figure 9.- Minimum Specific Fuel Consumption and Corresponding Engine r.p.m.

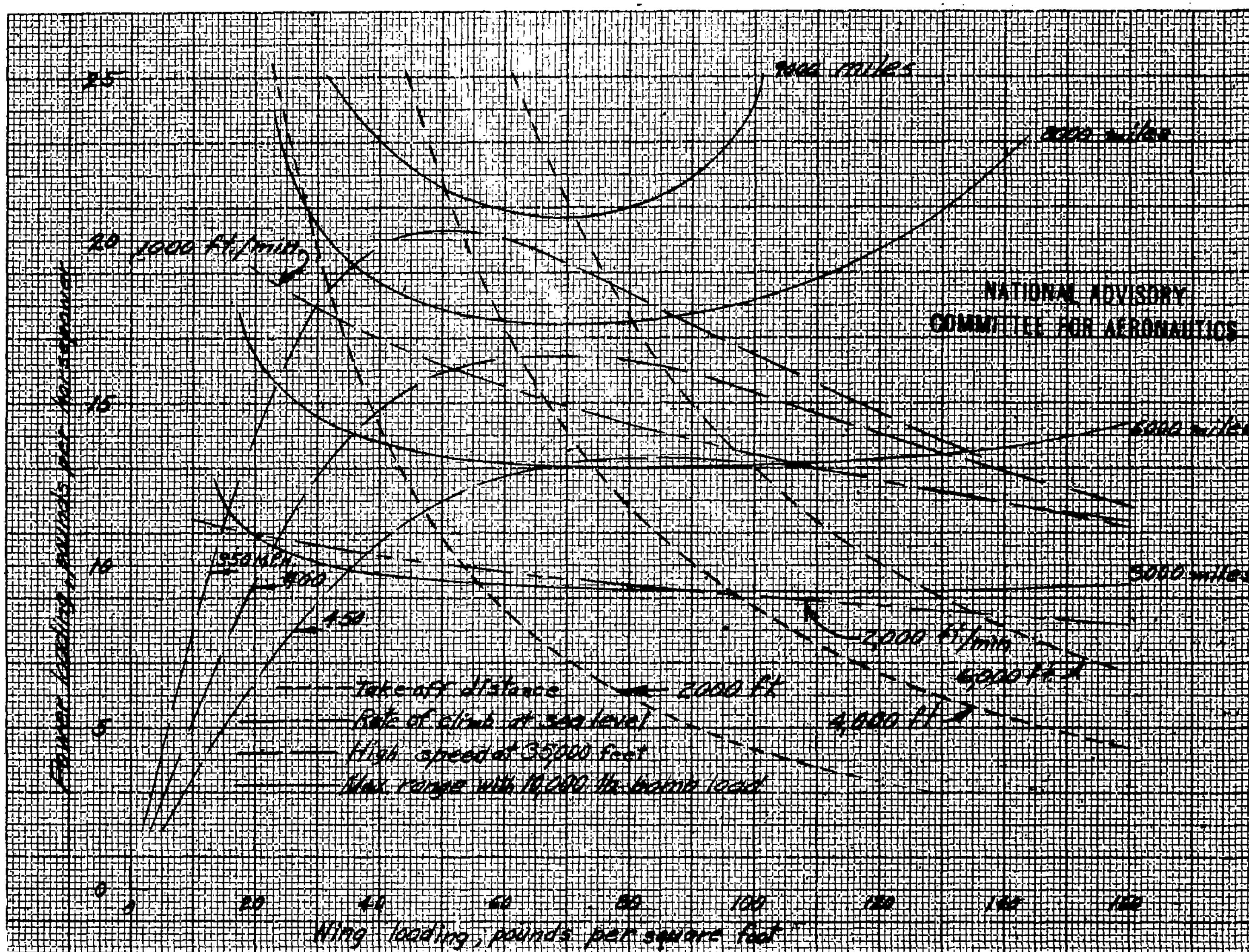

FIGURE 10a - PERFORMANCE SELECTION CHART FOR TWO-ENGINE BOMBERS. C_{D_0} = .0090 +

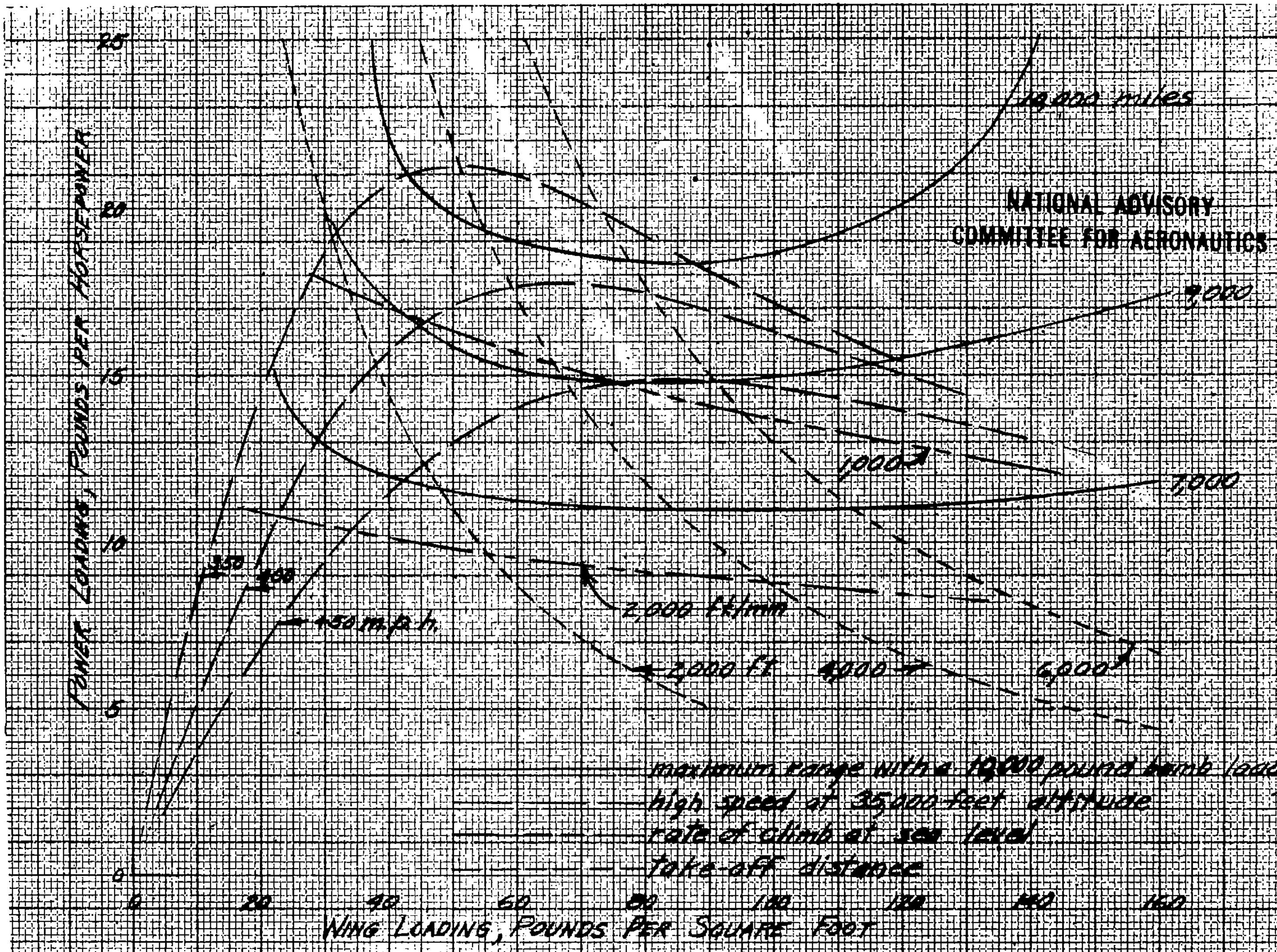

Figure 10b.- Performance Selection Chart for Four Engine Bombers.

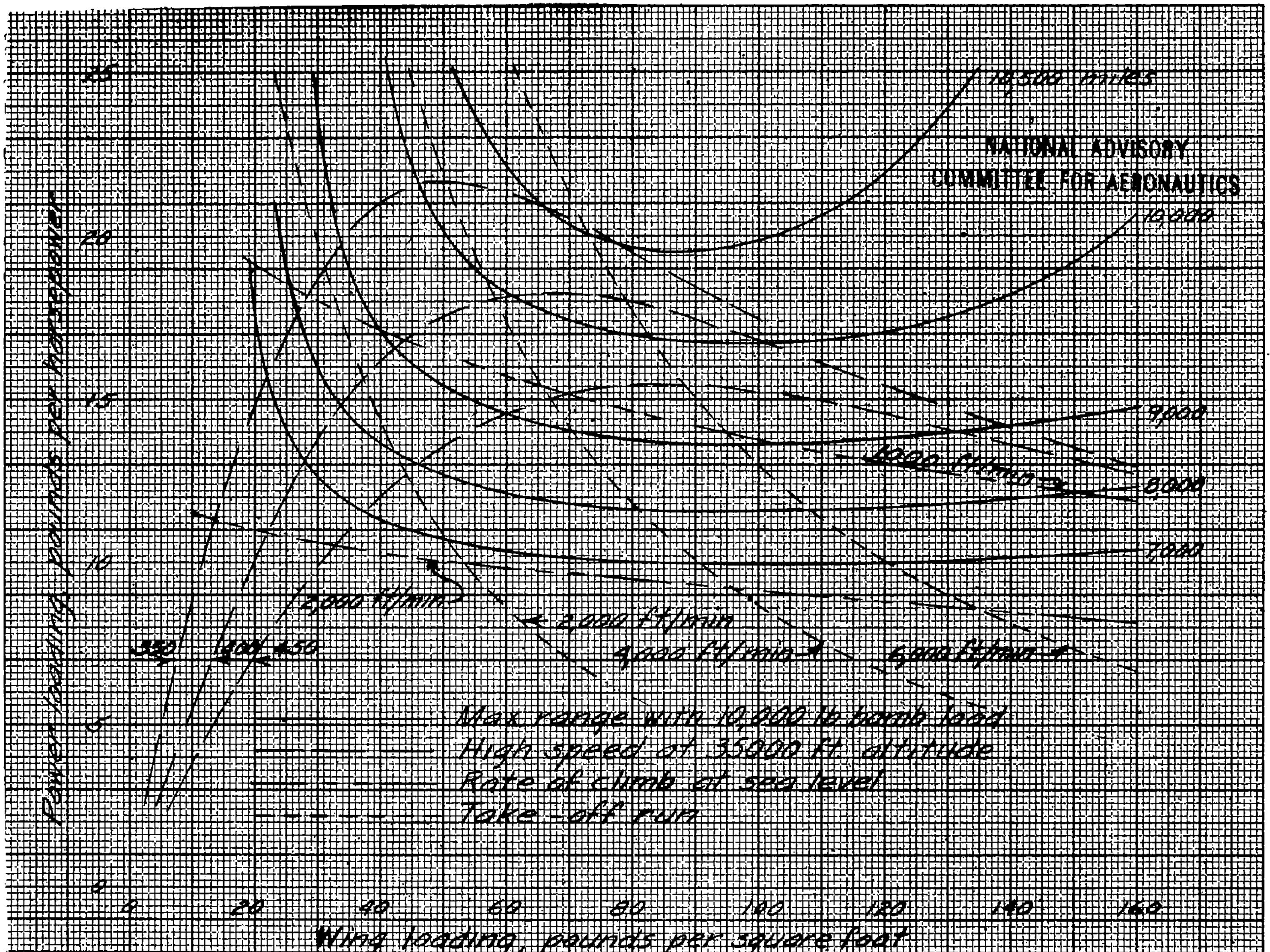

FIGURE 10c - PERFORMANCE SELECTION CHART FOR SIX-ENGINE BOMBERS [illegible]

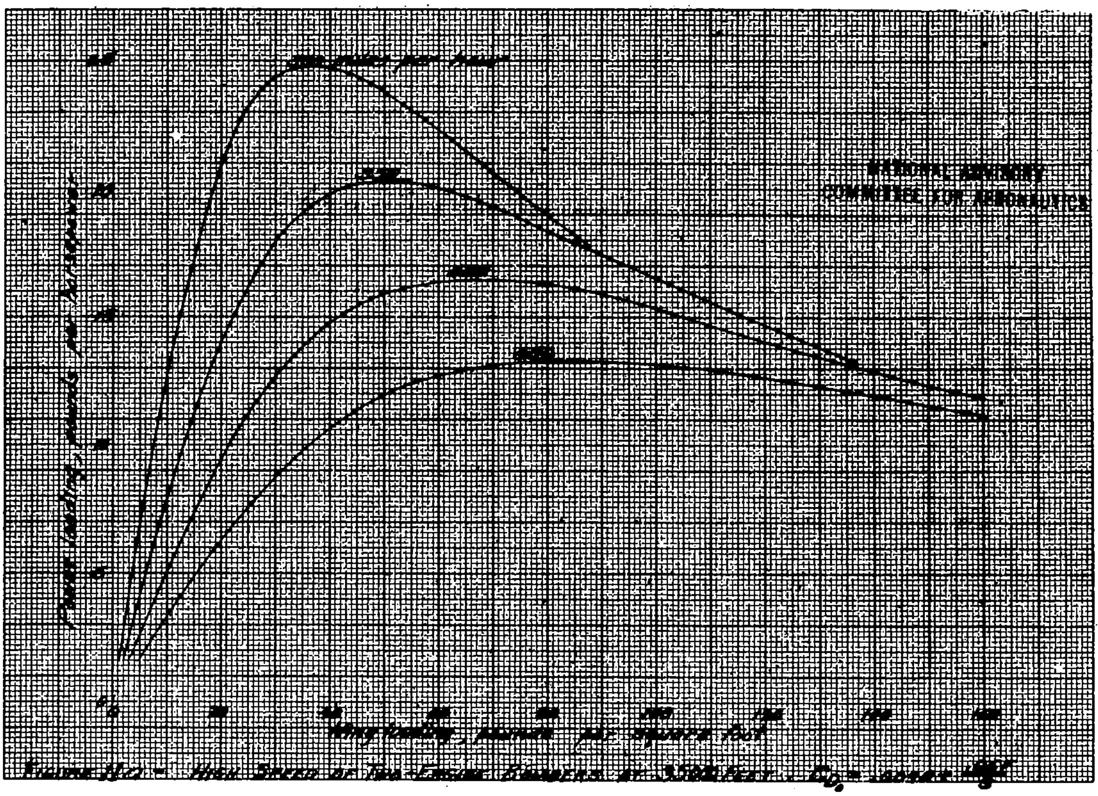

Figure 11(a) – High Speed of Two-Engine Bombers at 5000 Feet, C_{D_0} = [illegible]

KEUFFEL & ESSER CO. N.Y.

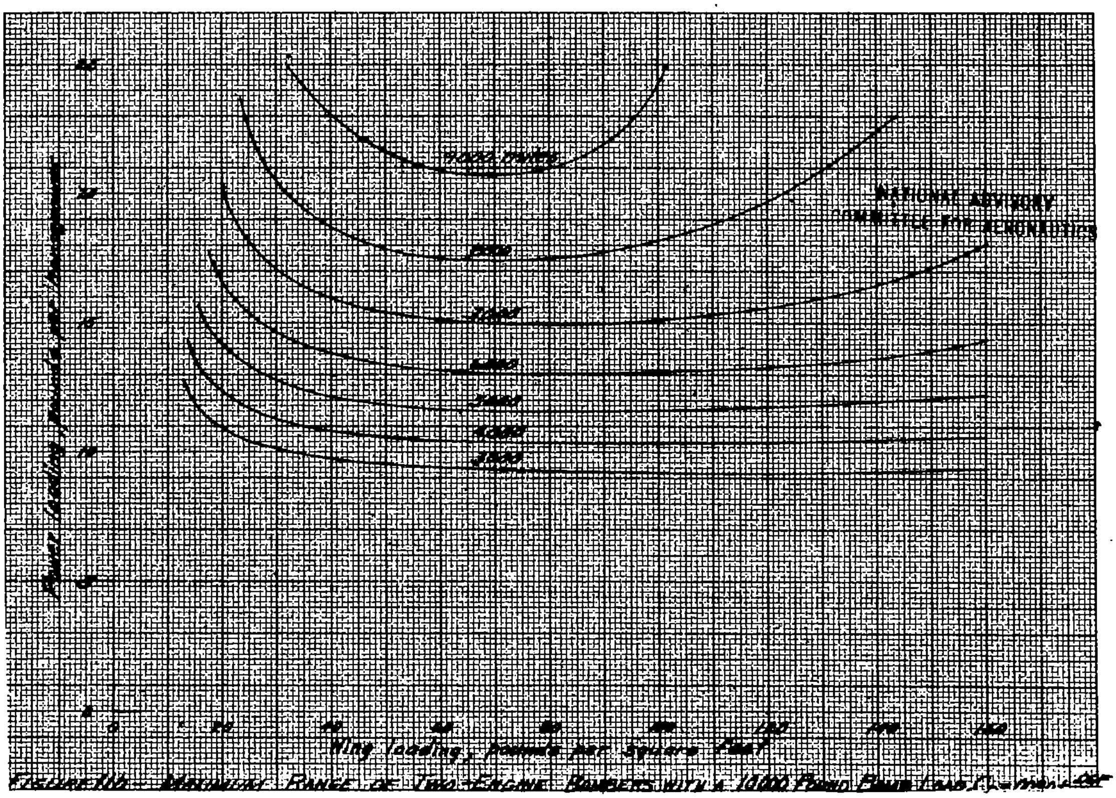

Figure 11(b) – Maximum Range of Two-Engine Bombers with a 10000 Pound Bomb Load, C_{D_0} = [illegible]

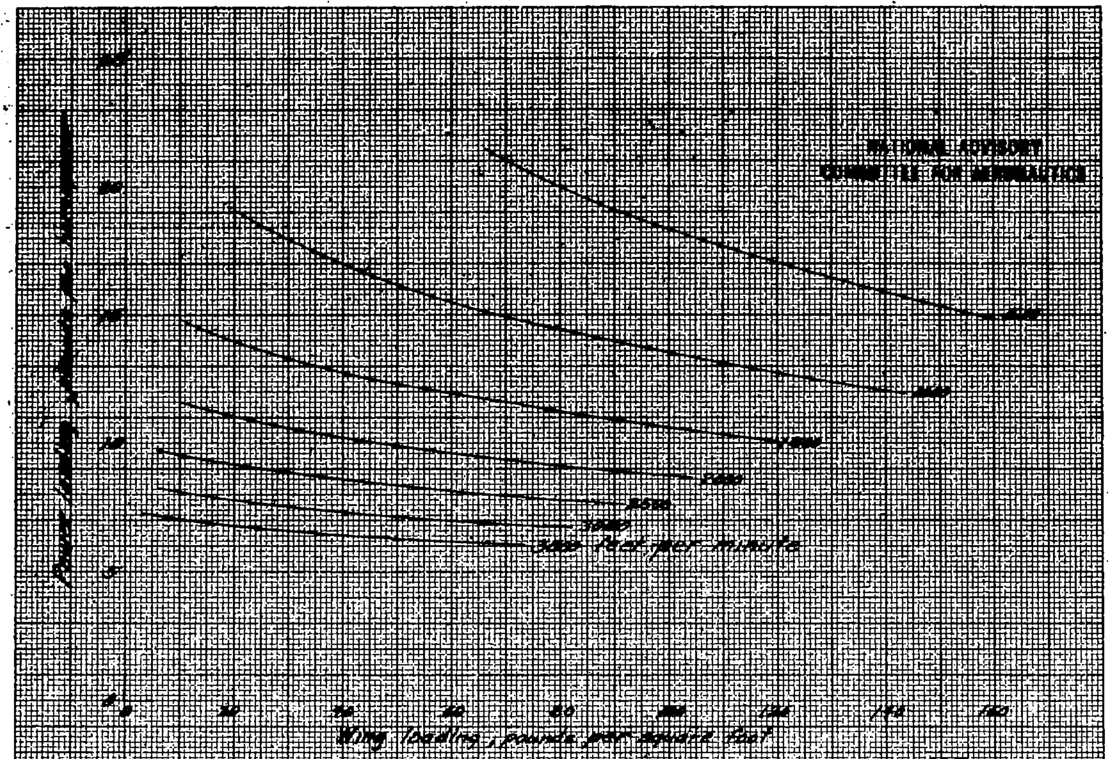

FIGURE 11c — RATE OF CLIMB OF TWO-ENGINE BOMBERS AT SEA LEVEL. $C_{D_0} = .0090 + \frac{.06F}{S}$

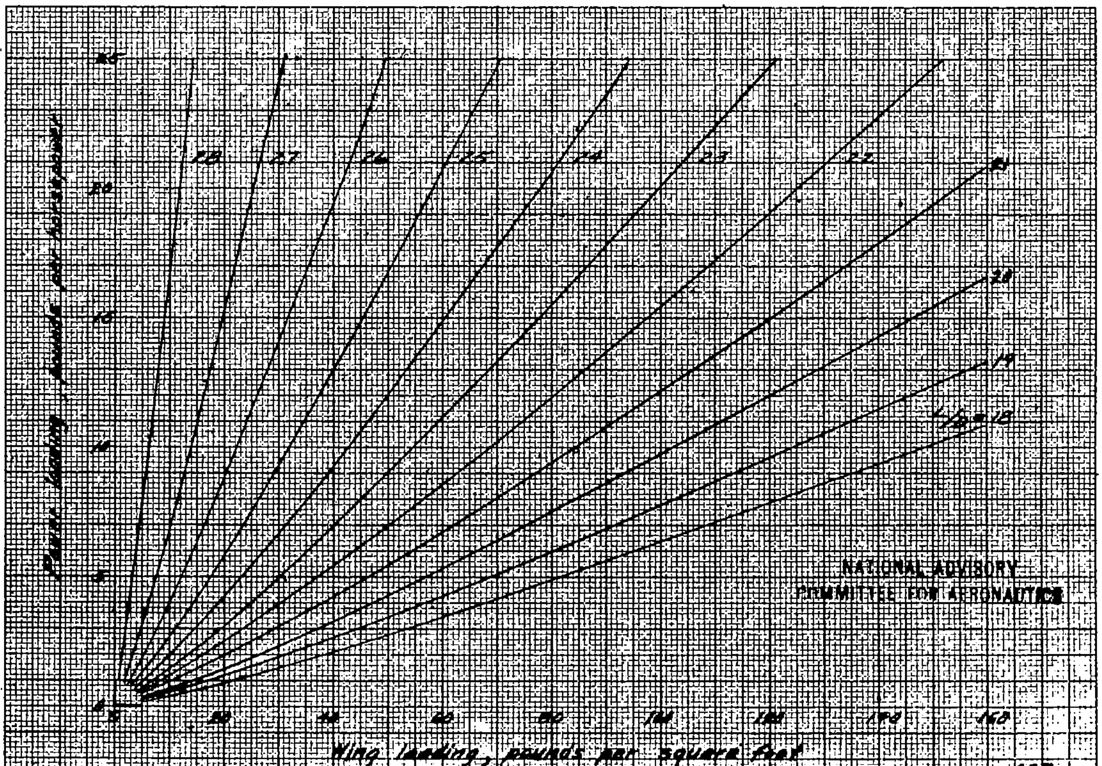

FIGURE 11d — MAXIMUM LIFT-TO-DRAG RATIO OF TWO-ENGINE BOMBERS. $C_{D_0} = .0090 + \frac{.06F}{S}$

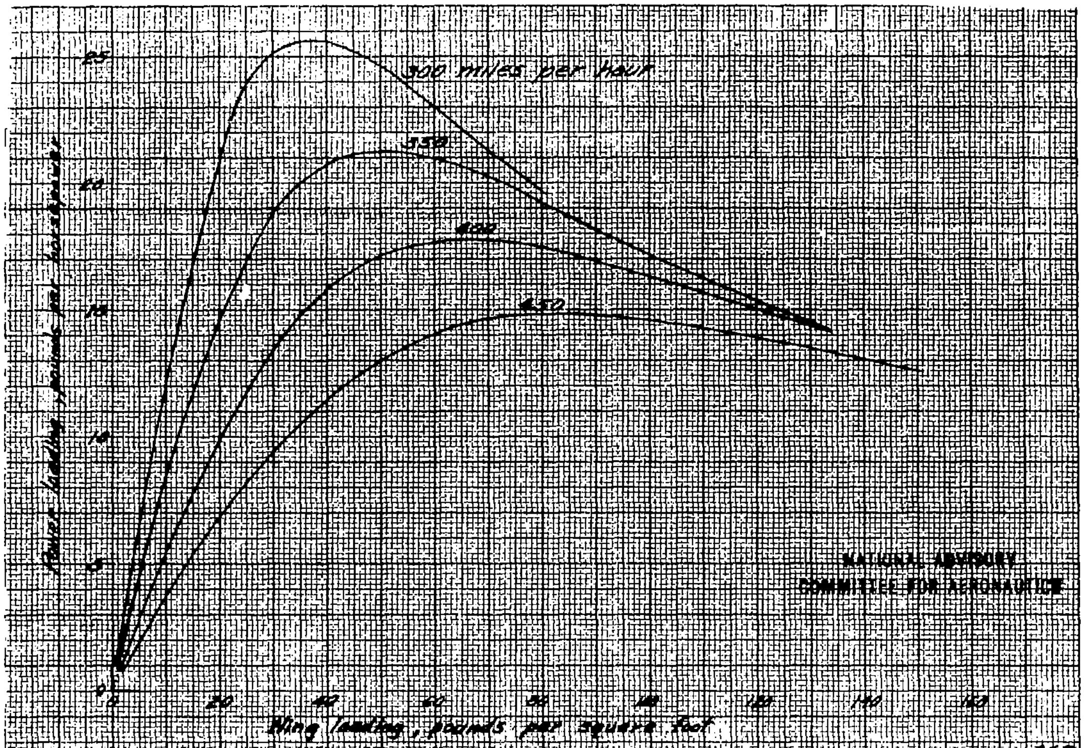

FIGURE 12a - HIGH SPEED OF FOUR-ENGINE BOMBERS AT 35,000 FEET. C_{D_0} = .0094 +

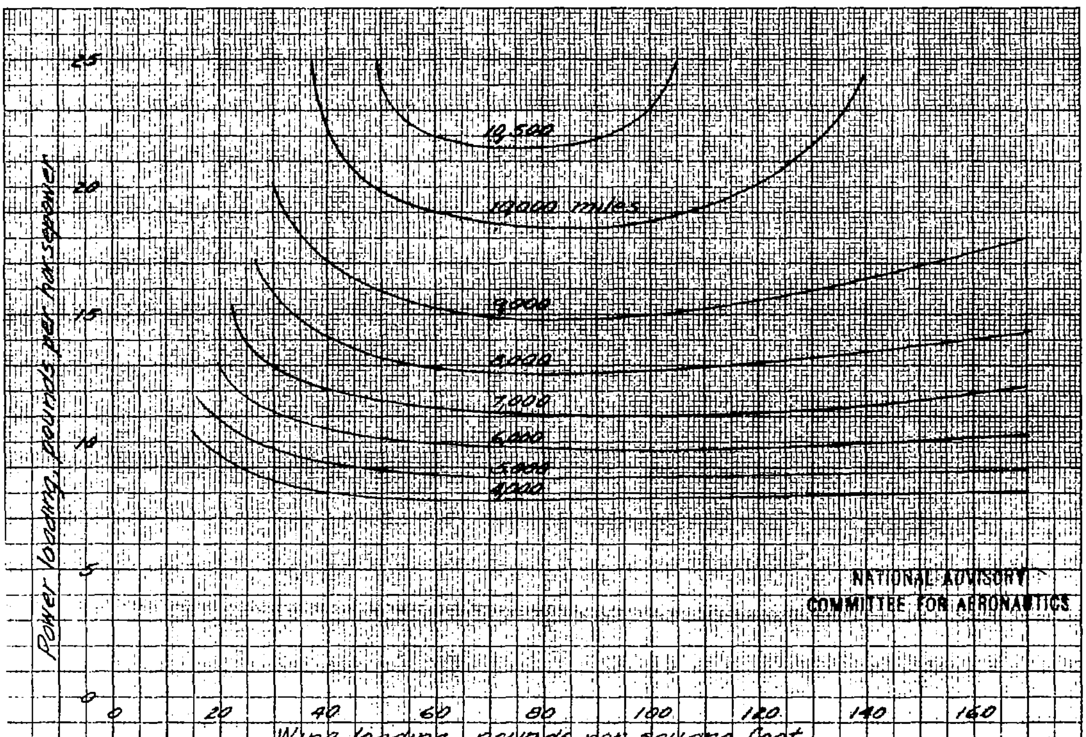

FIGURE 12b - MAX. RANGE OF FOUR-ENGINE BOMBERS WITH 10,000 LB. BOMB LOAD C_{D_0} = .0094 +

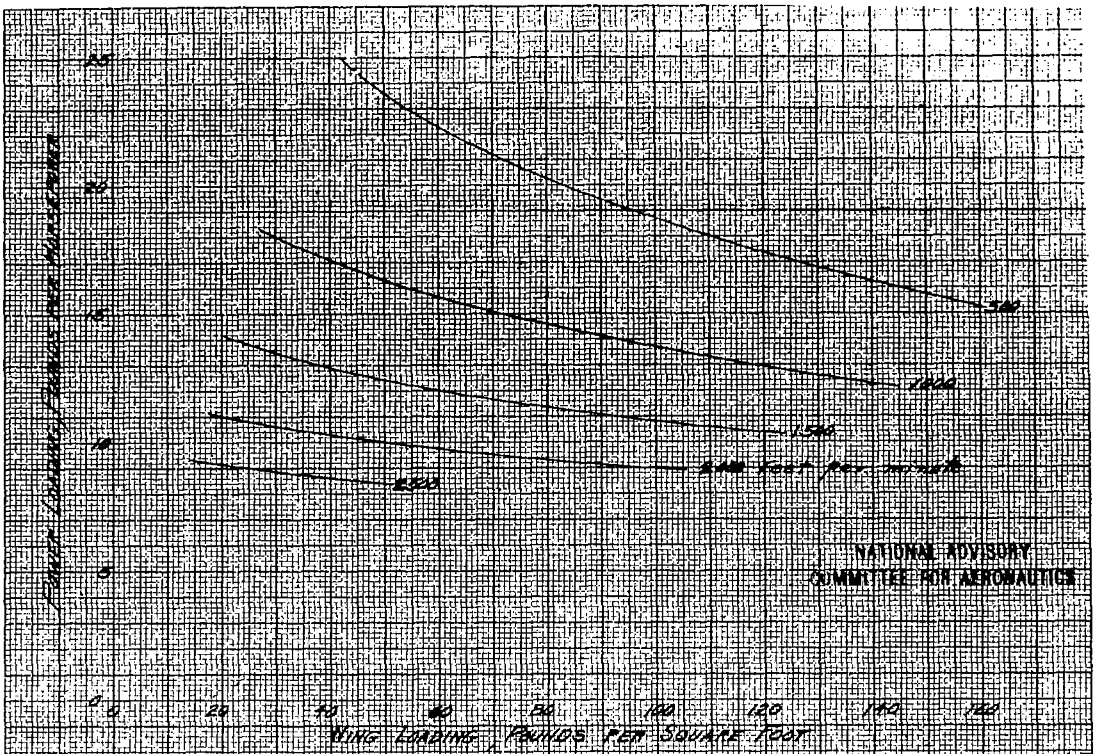

Figure 12c - Rate of Climb of Four-Engine Bombers at Sea Level. $C_{D_0} = .0090 + \frac{.26F}{S}$

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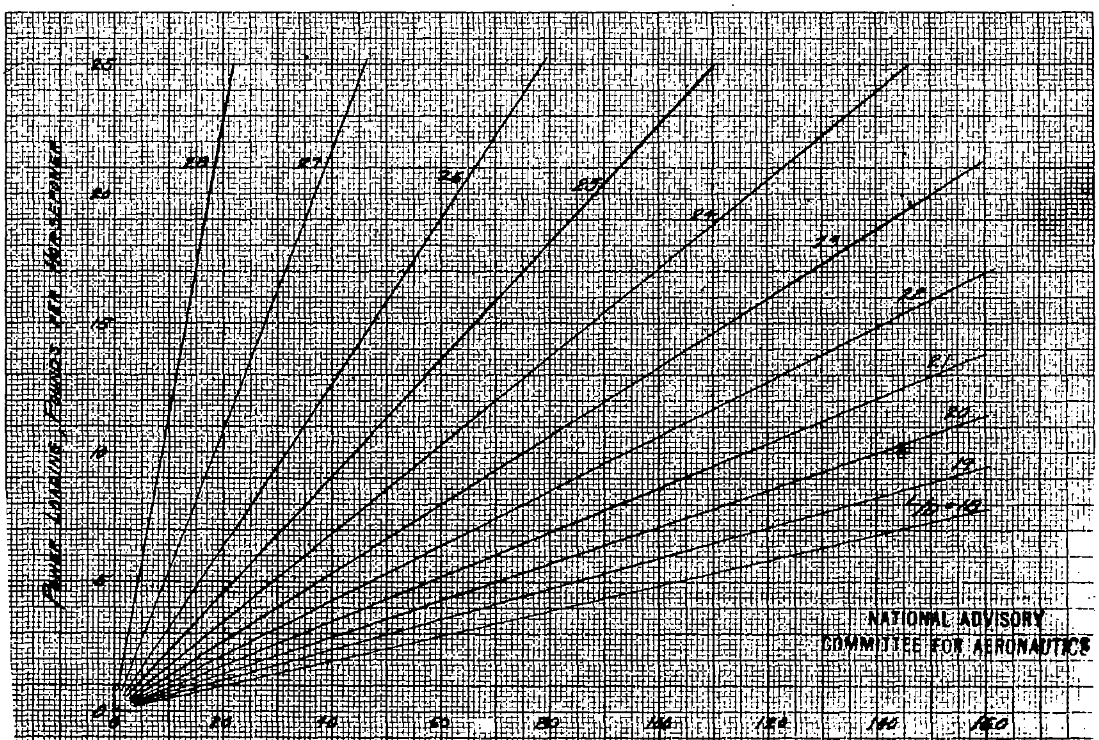
KEUFFEL & ESSER CO. N. Y.



Wing Loading, Pounds per Square Foot

Figure 12d - Max Lift to Drag Ratio of Four Engine Bombers. $C_{D_0} = .0090 + \frac{.06f}{S}$

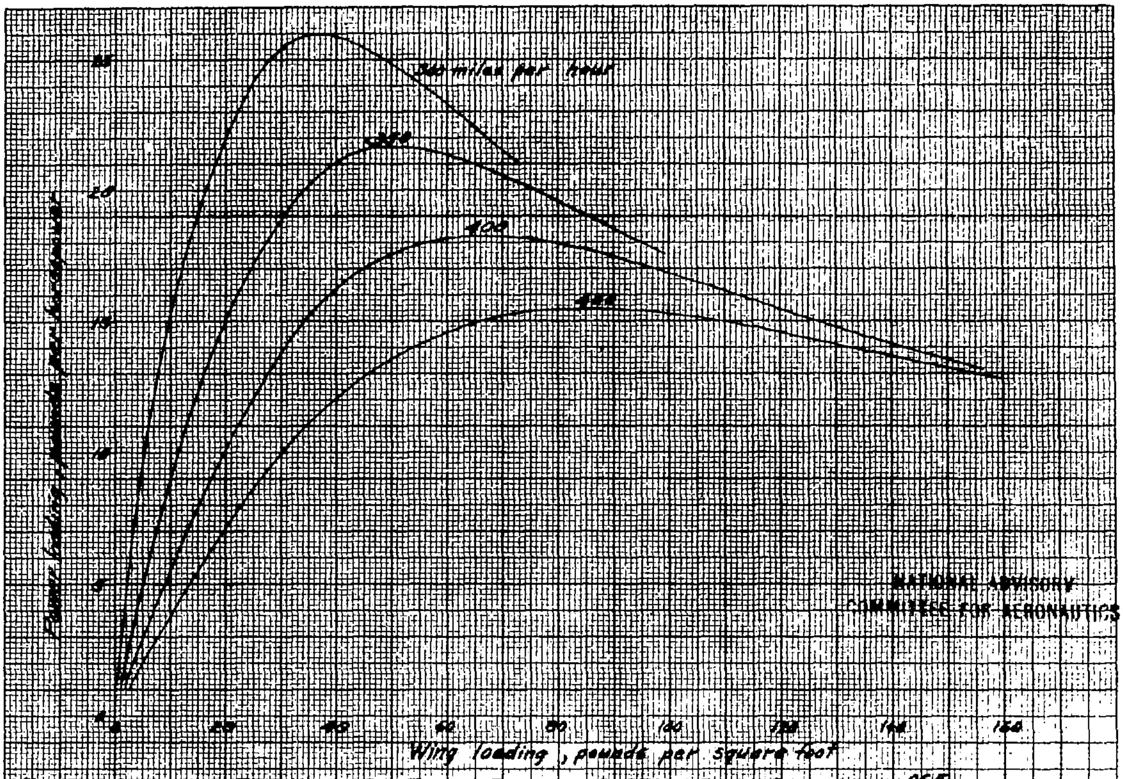


FIGURE 13a - HIGH SPEED OF SIX-ENGINE BOMBERS AT 35000 FEET. $C_{D_0} = .0090 + \frac{.05F}{S}$

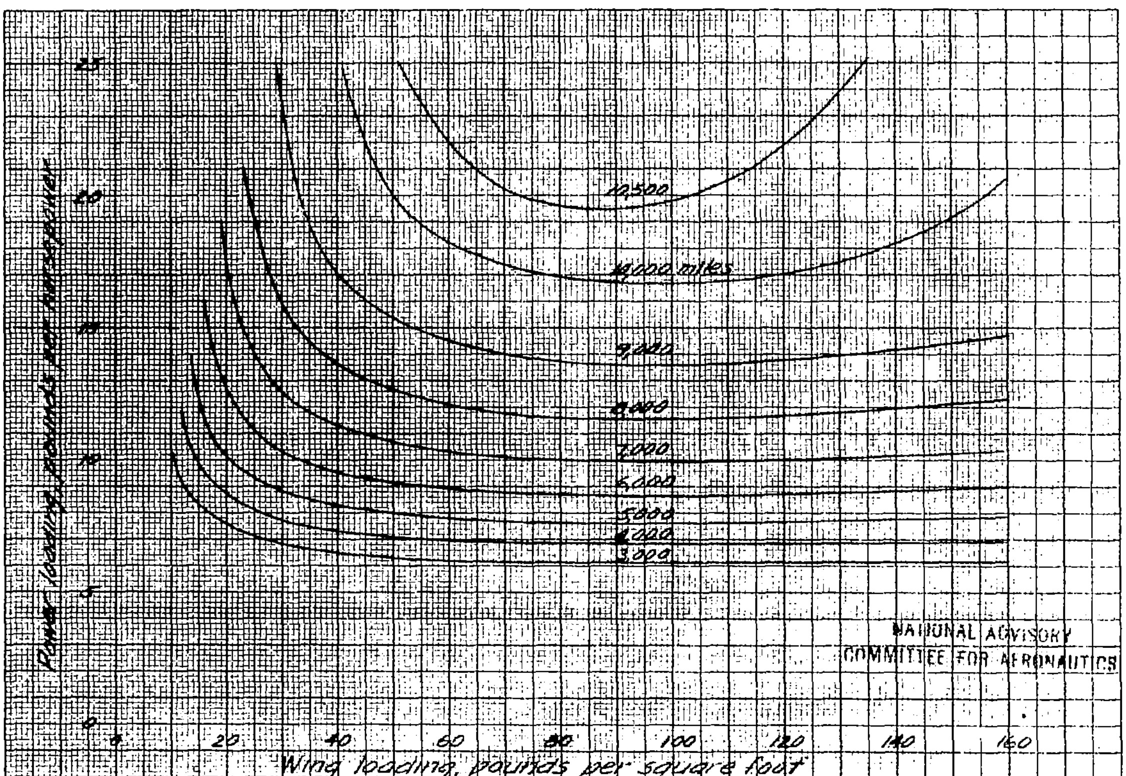


FIGURE 13b - MAX. RANGE OF SIX-ENGINE BOMBERS WITH A 14,000 LB. BOMB LOAD. $C_{D_0} = .0090 + \frac{.05F}{S}$

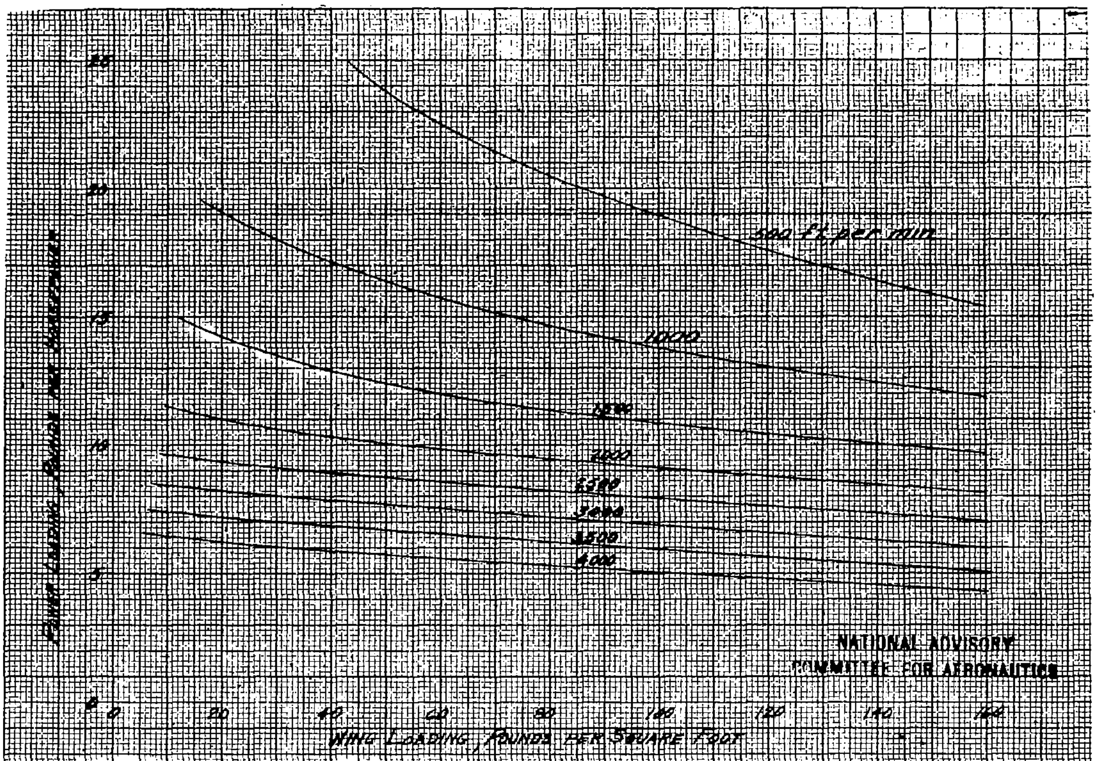


Figure 13 c - Rate of Climb of Six-Engine Bombers at Sea Level. $C_{D_0} = .0090 + .0065/S$

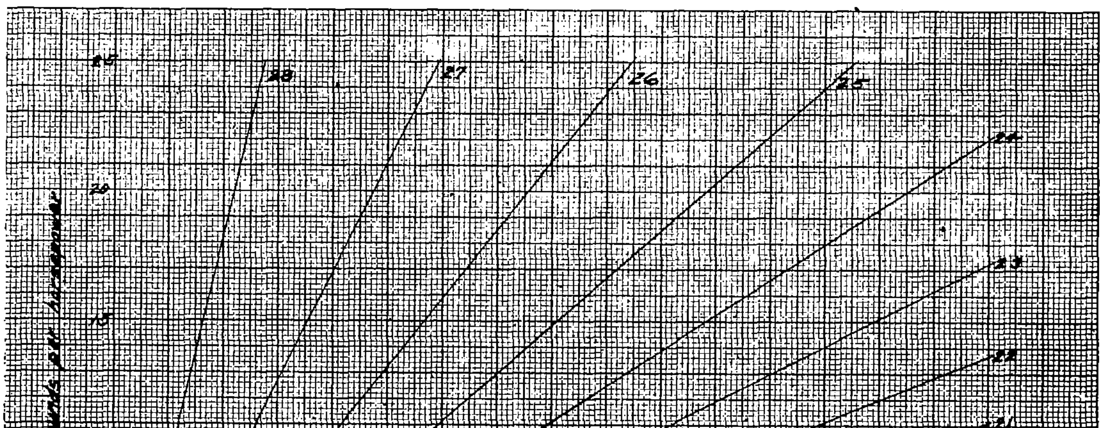


Figure 13 d - Maximum Lift-to-Drag Ratio of Six-Engine Bombers. $C_{D_0} = .0090 + \frac{.065}{S}$